TRANSACTIONS OF

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THIRD SERIES—VOLUME XLIX—SECTION IV

JUNE, 1955

OTTAWA
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PRESIDENTIAL ADDRESS

Geology in the Van

J. B. MAWDSLEY, F.R.S.C.

ABSTRACT

It is suggested that the early workers in the field of geology observed and recorded phenomena, which had they been recognized and appreciated by contemporary workers in other fields of science, might well have early accelerated important advances in these sciences. In a number of instances geology has had to wait for a sister science to progress far enough so that it could explain the phenomena encountered in field work. In spite of the great advances in all the sciences, and our greater general appreciation of these advances, there is much in the field of geology to accurately observe and explain of value and interest to all.

THE title may be misleading. It does not mean that geology is in the wagon and even less, on the wagon, but in the forefront, or lead. It is suggested that outstanding workers in the field of geology during the last century and a half have recognized phenomena of fundamental importance, which had they been appreciated by their contemporaries in the other sciences, might well have greatly accelerated advances in some fundamental areas of science. In many instances geology has had to wait for a sister science to progress far enough so that it could explain the phenomena encountered in geological field work.

Progress in one field of knowledge eventually reacts on every other to at least some extent. However, it appears that advances in geological knowledge have, in some important respects, been exceedingly slow of appreciation by workers in other fields. The few illustrations I am going to cite are, I am sure, well known to you all. We might take them as a present warning not to overlook advances being made in the other sciences. These examples point to the importance of obtaining all possible data and to the necessity of field work being done by able, keen, well-trained observers who will collect all available information in an unbiased and objective way.

William Smith (1769–1839), the self-taught surveyor, by the time he was twenty-four had decided that the strata of the centre and southwest of England dipped gently eastward and that they lay on one another like "slices of bread and butter." He took the greatest interest in the matter and untiringly recorded on maps and in notebooks the rocks, soils, and minerals he found. Before he was thirty he convinced himself that the strata could be traced, correlated, and separated by the "imbedded organic remains."

In 1815, he prepared, single-handed, a map eight feet long, based on an amazing number of observations in the field—"A Delineation of the Strata of England and Wales, with part of Scotland."

Although others, like Lamarck, had suspected differences in successive fossil assemblages, it was for William Smith to grasp and use this evidence fearlessly. His abilities to observe, classify, and deduce were of the very highest order. No clear account has been given of what he thought about these successively different faunas. He did not have the advantage of an extensive formal education; it had been of the most limited kind, derived in the course of a few years at a village school, but his great natural ability and insatiable curiosity must have resulted, on his part, in some most interesting speculations with respect to the changing faunas. This was many years before Charles Darwin published his momentous book, *The Origin of Species*, in 1859. Darwin saw great support for his theory in the fossil succession. Yet, "Strata" Smith, the field geologist, used the facts of evolution long before a reasonable theory had been advanced for their explanation.

When William Thomson, later Lord Kelvin (1824–1907), the distinguished Scottish physicist, in 1846 published his calculation of the time of the first consolidation of the crust of the earth as something between 20 and 400 million years, probably 100 million years, there was a fairly general acceptance of this pronouncement. It is now known that the age was calculated on wrong physical assumptions. Nevertheless it was generally accepted with alacrity by most thinking people of that day as a much more likely figure than that given by Archbishop Usher who in the seventeenth century gave the date of creation as 4004 B.C. There were people well acquainted with the geological record, like Charles Darwin (1809–1882), who were unable to accept Lord Kelvin's figure. Darwin in 1869 said, "I am greatly troubled at the short duration of the world according to Sir W. Thompson." Darwin, besides being rightfully regarded by the biologists as one of themselves, was also one of us. During the five years he was naturalist on H.M.S. *Beagle*, and later, he saw many fossiliferous strata and had a full appreciation of their meaning in terms of time. He and some contemporary stratigraphers could not believe that the thousands of feet of fossiliferous sediments that made up the geological column could have been laid down in an interval as short as that specified by Kelvin, who was quite unacquainted with this impressive record. If he had been aware of it, no doubt serious misgivings would have arisen in his able mind regarding the accuracy of the premises of his calculations.

The physicists' and chemists' estimate of age based on radioactive phenomena has finally caught up with that implied by the geologist. We have now got all the time we want. These figures for the age of different rock groups calculated in different laboratories, not the least of which are the ones operating in the cities of Toronto, Hamilton, and Ottawa, are both stimulating and disturbing, but there is little doubt that when we can correlate them better, they will prove extremely useful in ordering our data.

Mountain building has always, of course, interested geologists. Mountains are awe-inspiring and beautiful, and the roots of mountains, such as many of us have traversed in our North, are fascinating to study and speculate about. As a graduate student I found the literature dealing with the theory of mountain building very unsatisfactory. When I mentioned the subject to the late Professor C. H. Smyth, he remarked that he considered the articles dealing with the origin of mountains as the most unsatisfactory part of all geological literature; most theories were far too amateurish or fanciful.

There was, of course, a reason for this. Few of the requisite data upon which to base sound theories were then available. Since then, seismic and related data, as well as structural maps, have been rapidly accumulating and are forming a much sounder foundation for inferences regarding the nature and origin of mountains. Interesting theories are now being advanced by the geophysicists that are well worth considering and checking with the field facts. A valuable contributor to this sphere of work is the laboratory under the direction of one of our members, Dr. J. T. Wilson. The frustrations that one felt at trying to fit the obvious occurrences into an unlikely theory are passing, and theories based on physical and other data are starting to account for the observed geological phenomena.

William Logan (1798–1869) in 1846 mapped a group of rocks along the Ottawa River, which he subsequently found extended far to the east and west of it. He called them Laurentian gneisses and gave it as his opinion that their banded nature and other characteristics indicated that they were mostly highly altered sediments. Later workers considered that a high proportion of these rocks, whose composition resembles granite, were of igneous origin and their banding and gneissic structures were due to flowage while crystallizing, or that they were igneous rocks deformed after their consolidation. Now we generally agree that Sir William Logan was largely right; they are, in the main, highly altered sediments. Some of these bands, like the crystalline marbles, are obviously recrystallized limestone; other schists were once mud rocks; and the interbanded granitic gneisses are predominantly sandy and silty rocks whose composition has been much altered by some vast process of addition and subtraction. We who have had occasion to map and study them, who have sat on outcrops, rolled and lit cigarettes or smoked pipes, and pondered, have marvelled at the vastness and subtlety of the processes that resulted in their formation.

It has long been recognized by mine geologists that replacement of country rock by quartz or sulphides is a common occurrence, for example, the cubes of pyrite scattered over a distance of many feet in the greenstone wallrock of a quartz vein in a Porcupine gold mine; the silicification in many a mineral zone which has resulted in no change in volume; and the preservation in the greatest detail of the structures of the replaced sediments in the Sullivan ore. These replacements, or products of metasomatism, are analogous to the above-mentioned alterations or granitization suffered by the sediments deeply folded in mountain structures.

No chemical equation will stoichiometrically explain the above phenomena. The interchange of such great quantities of material without apparent volume change is explainable in no simple manner. In fact there was no adequate answer until crystal chemistry developed.

Crystal chemistry is the outcome of much thought and work with crystals that goes back a long way to the early workers in mineralogy, but crystal chemistry itself is relatively new, and might be said to have been the aftermath of the discovery in 1912 of the diffraction of X-rays by a crystal grating. This momentous discovery by Friedrick, Knipping, and Laue took the determination of crystal structure and molecular configuration out of the realms of speculation into that of accurate measurement. W. L. Bragg in 1920 discussed lattice dimensions in certain crystalline substances, thus laying the basis of the study of crystal chemistry. Since then, work in this field has travelled apace and such puzzling matters as isomorphous series have now an explanation. The contributors to this, and to the broad field of geochemistry, have been very many. It is impossible to list them here, but I must at least mention two groups: the notable group of Scandinavian scientists headed by such names as Vogt, Brogger, Goldschmidt, and Eskola; and those in the Carnegie Geophysical Institute in Washington. Now chemists, mineralogists, petrologists and others, talk in a useful manner about the radius of atoms or ions, interatomic distances, and the various ways the units are bonded in the crystal lattices. Even undergraduates mention in the most casual manner the silica tetrahedron.

An obvious outcome of crystal chemistry was the recognition that most ions and atoms can find their way with varying degrees of ease through crystal lattices, or around their ragged edges where one crystalline grain meets another. Quite recently measurements have been made on the rates of diffusion of some elements, but none, so far as I know, of particular interest to geologists. The rates of diffusion in solids that have been measured have shown variations between substances, but all are very slow and take a long time to go an appreciable distance. However, there is one thing that geologists have plenty of, and that is time. Even though diffusion is infinitely slow, it has been inferred that by this process granitization could affect a mass many kilometers thick in 200 million years—and what is 200 million years to us?

Shades of the first Director of the Survey are here with us. The quiet, observant, indefatigable Sir William Logan recognized that the gneisses along the Ottawa were highly altered sediments almost a century before chemical theory had advanced sufficiently to explain this alteration. Possibly if chemists had been acquainted with gneisses a century ago, work in certain branches of chemistry might have been initiated much earlier.

There are many other geological facts not yet fully explained, such as the relationship of certain ores with certain rocks—tin with granite and chromite with ultrabasic rocks; the rapid and complete disappearance of the ammonites at the end of the Cretaceous; and rhythms in sedimentary

assemblages like that of the Pennsylvanian of Illinois and adjacent states which are due to some cyclic physical phenomena.

Not only do we each in our special field in geology have to keep acquainted, as far as we can, with advances in the other fields of geology, but also with advances in the basic sciences, with the object of throwing light on problems we already have and others that are bound to be discovered in the future. We must, also, be even more diligent in obtaining the necessary geological data.

Let us make no mistake. The bulk of the evidence must be obtained in the field by people trained to observe and having an eye for the unusual. After thorough study of the field evidence with the aid of laboratory methods and correlation with geophysical and other data, will come deductions, hypotheses and theories. Then, of course, comes the final step in the scientific process—verification; the results of all this work must fit the field facts. Neglecting to observe properly in the first instance, or to check properly in the final steps, is bound to result in incomplete or erroneous conclusions.

Our sister sciences of biology, physics, and chemistry might have progressed more rapidly if they had been acquainted with the findings of some of the early geologists. The leaders in this group were extraordinarily objective in their work. Their abilities to observe, record, and deduce were of the highest order. These traits are still needed today and must be developed in the forthcoming geologists.

In many ways we are in the Golden Age of Geology, and doubly so in Canada where there is so much to do. Dr. George Hanson, the present Director of the Geological Survey of Canada, a few years ago made the statement that at the rate we were then going it would take about 700 years to complete an adequate geological map of the Dominion. Results have accelerated in recent years in the reconnaissance phases of mapping, at least. Aerial photographs, aeroplanes, and especially helicopters are saving a lot of time and shoe leather. Researches in the broad fields of geochemistry and geophysics are progressing apace and supplying much valuable information. But, in spite of all this, new unexplored horizons will stretch in every direction for a long time to come. As far as geologists are concerned, the Second Elizabethan Era has the same quality as that of the stirring days of the reign of the first Elizabeth when there was much room for those who wished to be in the van.

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SECTION FOUR

Archean Monazite in Beach Concentrates, Yellowknife Geologic Province, Northwest Territories, Canada

R. E. FOLINSBEE*

Presented by P. S. WARREN, F.R.S.C.

ABSTRACT

Gneiss-derived monazite occurs as a minor constituent of small, well-sorted beach placers formed from esker sands on the south shore of Yamba Lake, Yellowknife geologic province, Northwest Territories. Magnetite, ilmenite, and almandite garnet are the dominant minerals of the monazite-bearing beach concentrate. Other heavy minerals identified include andalusite, apatite, biotite, brookite, epidote, hornblende, kyanite, olivine, pyroxenes, rutile, scheelite, sphene, sillimanite, spinel, staurolite, tourmaline, and zircon; of these only kyanite has not previously been recognized in rocks of the Yellowknife province. The injection-gneiss or migmatite, source of the monazite, has been assigned to the Archean (2200-2400 million years) on the basis of field relations confirmed by potassium-argon and other age-dating methods. The relation of the gneiss to other rocks of the Yellowknife continental nucleus has been established.

Introduction and General Geology

DURING 1947, in the course of reconnaissance field mapping for the Geological Survey of Canada in the barren grounds 250 miles northeast of Yellowknife, Northwest Territories, sands were collected from esker-derived beach placers. Two of these sands, a monazite-bearing sand from Yamba Lake and a monazite-free sand from Exeter Lake, Lac de Gras map-area, together with the associated rocks, were studied at the University of California, Berkeley, where research facilities were kindly made available to the writer.

W. F. Fahrig, G. A. Vary, G. T. McCallum, A. R. Nielsen, and H. Greiner assisted in collection of samples and field mapping. Professors Turner, Pabst, Gilbert, Verhoogen, and Meyer, of the University of California, and Professor Hutton of Stanford University were most helpful in suggesting solutions to problems in their particular fields. Professor Reynolds and Mr. Lipson of the Department of Physics, University of California, made the potassium-argon age determinations reported in this paper, and Doctors Larsen, Gottfried, Stieff, and Stern of the United States Geological Survey, Washington, contributed data leading to age determinations of the monazite and zircon.

*J. H. Reynolds and J. Lipson, of the Department of Physics, University of California, Berkeley, with whom the writer has been collaborating, deserve full credit for the principal research contribution of this paper—the table of potassium-argon ages.

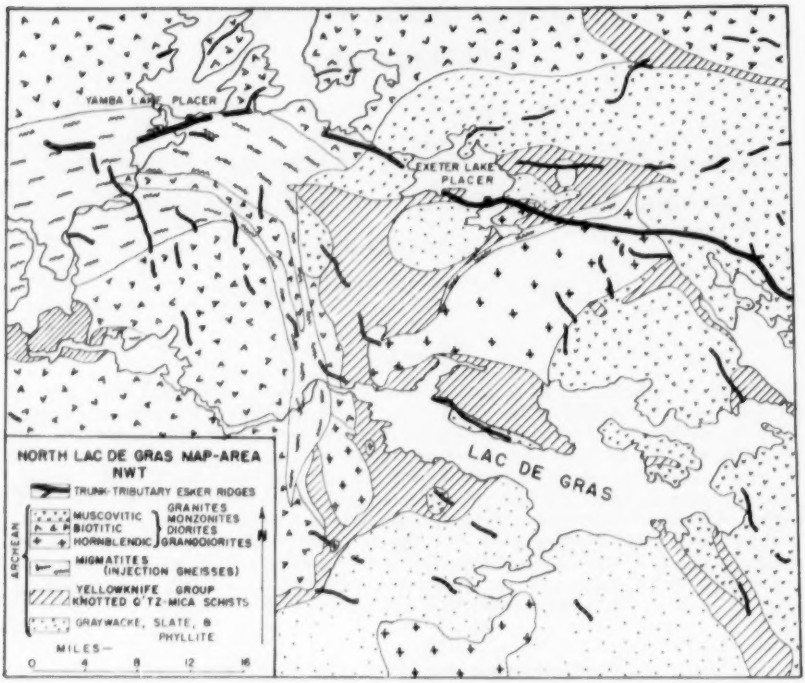

FIGURE 1.—North Lac de Gras map-area, 64°15′ to 65°00′ North, 110°00′ to 112°00′ West, Northwest Territories, Canada.

The map-area (Figure 1) lies almost in the centre of the Yellowknife Geologic Province (Jolliffe, 1948; Gill, 1949). Within the map-area, as throughout the Yellowknife province, the Archean Yellowknife-group graywackes and argillites have been intruded by granitic rocks ranging in composition from hornblende diorites to muscovite pegmatites. In general the hornblendic intrusives appear to be older and the muscovite-bearing intrusives to be younger. Most of the intrusives are probably of Archean age, though there has been much debate as to the extent of the Proterozoic granitic intrusions in the western part of the Canadian Shield (Henderson, 1948). Age dating appears to support the contention of Lord and Barnes (1953) that all of the granitic rocks of this part of the Yellowknife province were intruded during a single period of orogeny which was apparently of very short duration.

The hornblende-bearing intrusives had the least effect on the pelitic and psammatic Yellowknife group sediments; thermal aureoles around these intrusives are small or absent. The biotite granodiorites and muscovite granites have altered the graywackes and argillites to nodular or knotted schists, and to paragneisses. Thermal metamorphic aureoles around the muscovite granites are very prominent, up to eight miles in width.

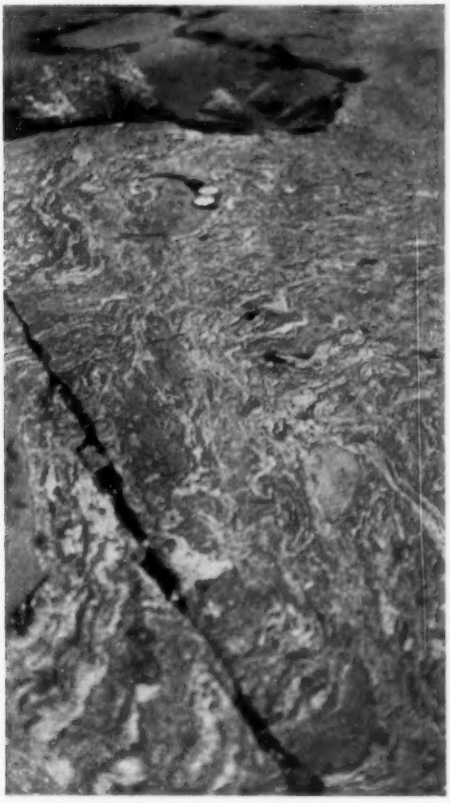

FIGURE 2.—Injection-type migmatite, south of Yamba Lake, Lac de Gras map-area. Geological Survey of Canada photograph.

The paragneisses are migmatitic, strongly foliated rocks developed from deeply buried sediments enveloped by granitic masses. Lenses of light-coloured igneous-like rocks (muscovite and biotite granites) are developed along the foliation planes of the gneiss (Figure 2). They might equally well be attributed to granite injection or to diffusion of granitic constituents from the sediments by anatexis, depending on whether one approaches the migmatite in the mood of a magmatist or a transformationist (Turner and Verhoogen, 1951). On the published map (Folinsbee, 1948) the gneisses are called injection gneisses, but to avoid a controversial point (Alcock, 1949), they will be called migmatites in this paper.

The migmatite, however it was formed, exists as a rock mass covering an area of 500 square miles. The rock is of variable composition, consisting on the average of 40 per cent oligoclase feldspar, 30 per cent quartz, 20 per cent biotite, accessory monazite, rutile and hyacinth cored zircon, with minor muscovite, chlorite and iron oxide as alteration products, and in

places accessory blue cordierite, white fibrous sillimanite, bladed kyanite, black graphite flakes, and almandite garnet crystals suggestive of sedimentary origin. The granite-like lenses, averaging one foot in length and two inches in width are composed mainly of alkalic feldspar, quartz, and muscovite mica. The migmatite is comparable with the Lewisian gneisses of Scotland, as described by Read (1931) and Mackie (1925), and with the Grenville gneisses as described by Engel and Engel (1953).

Glacial and Recent Geology

The map-area lies in the Coppermine ice-drainage basin, where the main ice flow and fluvio-glacial drainage is to the northwest, as indicated by glacial striae, long axes of drumlins, and the trunk and tributary esker-ridge pattern. The principal, or trunk, esker can be traced across the map-area, from north of Lac du Sauvage, south of Exeter and Yamba Lakes. The same esker has been traced from aerial photographs and by field mapping for 320 miles (Wilson, 1939, 1945; Lord and Barnes, 1953). The trunk esker rises as much as 80 feet above local lake level, and in places is 500 feet wide (Figure 3). The esker sands and gravels are of variable size, from boulders to fine sand; though there is usually a high degree of sorting in any one part of the esker.

Winds are predominantly from the northwest, and, in embayments along the south shores of both Yamba and Exeter Lakes, black and purple sands have been washed from the esker sands and gravels by wave action. The high-gravity sand layers are neither thick nor extensive—the ones noted were 50 to 100 feet long, 3 to 10 feet wide, and about 6 inches in thickness. The total tonnage of black sand is small. These beach placers are very well

Figure 3.—Looking east along the trunk esker, Exeter Lake. Black beach placers occur in the cove, centre foreground. Geological Survey of Canada photograph.

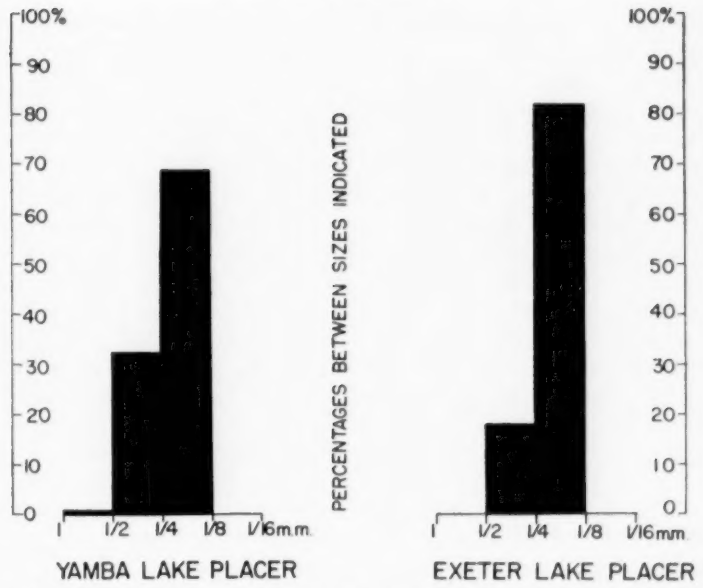

FIGURE 4.—Well-sorted fine and medium grained sands of the beach placer, Lac de Gras map-area, Northwest Territories.

sorted fine sands (Figure 4), and contain less than 1 per cent light contaminants, mostly quartz and feldspars.

SAMPLE TREATMENT AND MINERAL DESCRIPTIONS

Field samples were weighed and screen sized; the dominant size fraction (60-65 mesh) was selected for the most intensive study. This fraction was considered to be representative of the heavy mineral suite, and most suitable for magnetic separation and immersion-mount study. Finer size fractions were examined for such minerals as zircon. With the Frantz isodynamic separator the heavy minerals were separated into fractions of varying magnetic susceptibility (magnetite was first removed with a permanent magnet). These fractions were examined with a binocular microscope, and individual minerals were separated on the basis of colour and other physical properties. Permanent mounts of all separates were made in aroclor (n 1.66). Identity of separate minerals was established using immersion mounts and other tools of the sedimentary petrologist. In general, the methods of study suggested by Hutton were followed (Hutton, 1950, 1952). Only the anomalous optical properties, or those of compositional significance, will be reported in this paper.

Andalusite is fairly abundant in the non-magnetic fraction, occurring as angular grains with characteristic pink to light green pleochroism. The chiastolite variety of andalusite is a common constituent of the metamor-

phosed Yellowknife group pelites; and mauve-coloured crystals of andalusite without carbonaceous inclusions are found in quartz veins in the schists.

Apatite, blue-green under the binocular microscope, is an abundant mineral in the non-magnetic fraction of the beach placers. Index determinations (N_o 1.637, N_e 1.632 $\pm$ 0.002) suggest that these are fluor-apatites. Blue-green apatite is a characteristic accessory of the muscovite granites of the eastern part of the map-area, and, as is to be expected, it is more abundant in the Exeter Lake than in the Yamba Lake placers.

Biotite is a minor constituent of the beach placers; since it is an abundant constituent of nearly all the rocks contributing to the esker sands, it is probably rafted out of the eskers during fluvio-glacial sorting, or winnowed out with the light minerals during the placering period.

Brookite grains, light golden-brown in colour, were picked from the non-magnetic fractions and identified on the basis of index and interference figure (Brammal, 1928). Though brookite has not been recognized in thin sections from the rocks of the map-area, it probably occurs as a minor accessory in the granites or gneisses (Mackie, 1928).

Epidote is abundant in the moderately magnetic fractions of the Exeter Lake placers. In the field epidote was observed as an accessory in the granodiorite southeast of Exeter Lake, and with hornblende in the hornblende quartz-diorites south of Exeter Lake; these are undoubtedly the source of the epidote in the Exeter Lake placers. Apparent absence of monazite in the Exeter Lake placers may be explained on the basis of this association, for as Mackie (1928, p. 23) observes, where hornblende or sphene appear in a granitic rock, monazite is never present.

Garnet, of the almandite variety, pink to reddish pink in colour, is an abundant to predominant mineral of the beach concentrate, comprising 35 per cent of the Yamba Lake and 80 per cent of the Exeter Lake placers. Garnet is a very common mineral in the Yellowknife meta-sediments, and occurs also in marginal phases of the biotite granodiorites (Miller, Barnes, and Moore, 1951) and in the muscovite granite pegmatites. Light purplish

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Plate I. Typical heavy detrital minerals, Lac de Gras map-area. All figures are at the same magnification (×135) and were drawn from grains immersed in aroclor (n 1.66).

1. Zoned zircon showing very extensive fissuring. Yamba Lake beach sand.
2. Rounded hyacinth core in slightly zoned zircon. Migmatite, Yamba Lake.
3. Euhedral hyacinth core with overgrowth of zircon or malacon. Migmatite, Yamba Lake.
4. Elongate, fluorescent, euhedral zircon with apatite inclusions, from muscovite granite. Prosperous pegmatite, Yellowknife.
5. Euhedral tablet of monazite, moderately fissured. Yamba Lake beach sand.
6. Elongate monazite crystal, showing poor development of cleavage. Yamba Lake beach sand.
7. Rounded monazite crystal. Migmatite, Yamba Lake.
8. Clear yellow monazite, from muscovite granite. Prosperous pegmatite, Yellowknife.
9. Prismatic crystal of tourmaline with rhombohedral terminations. Exeter Lake beach sand.
10. Staurolite crystal showing sieve structure. Exeter Lake beach sand.
11. Bladed crystal of kyanite. Exeter Lake beach sand.

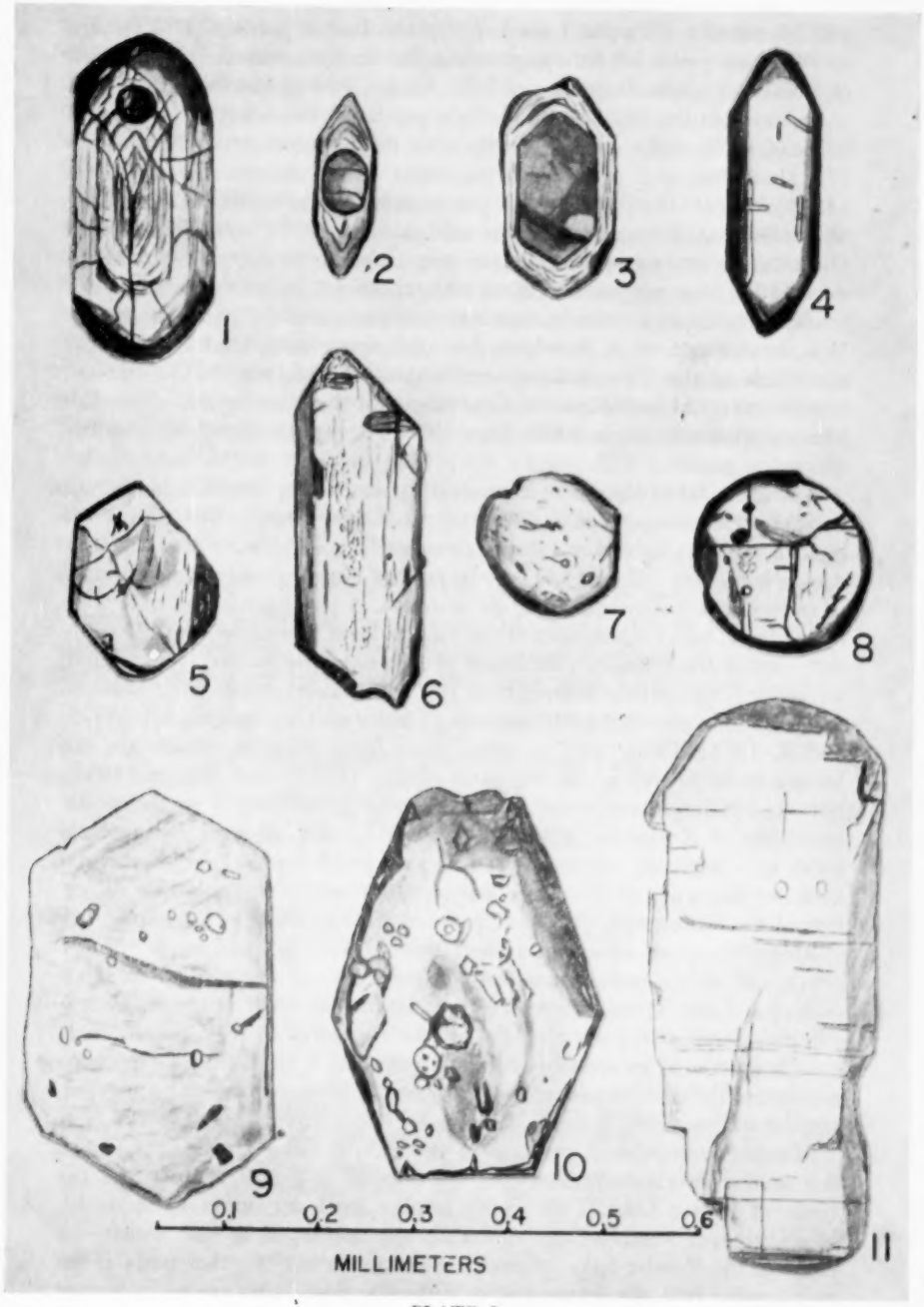

PLATE I

pink garnet of the Yamba Lake beach placer has an index of 1.795 and a specific gravity of 4.17; reddish garnet in the same concentrate has an index of 1.800 and a specific gravity of 3.97. An analysed almandite garnet from a migmatite in the Yellowknife geologic province (Folinsbee, 1941) has an index of 1.798 and a specific gravity of 4.109; its molecular composition is 74.0 almandite, 24.0 pyrope, 1.5 spessartite, 0.5 grossularite. Ford's curves (1915) indicate the purplish pink garnet to be an almandite with considerable spessartite in the molecule; the reddish garnet to be an almandite with about 20 per cent pyrope and 20 per cent andradite in the molecule. Miyashiro (1953) has suggested that the manganese-rich garnets represent lower grade metamorphism than manganese-poor garnets of the pyralspite group. It is interesting to note that both low and high grade metamorphic rocks contribute to the Yamba Lake concentrates (Henderson, 1943), though it is unlikely that in the Lac de Gras map-area the lowest grade schists fall into the chlorite zone, in which Turner (1951) reports abundant accessory spessartite garnet.

Kyanite is fairly abundant to abundant, particularly in the larger screen sizes of the non-magnetic fraction of the beach placers. The grains are typical, angular, light-blue kyanite cleavage fragments, with some carbonaceous inclusions (Plate I). The mineral has not previously been reported in rocks of the Yellowknife geologic province. A few grains of kyanite were recovered in heavy separations of the Yamba Lake migmatite, and it is likely that most of the kyanite in the beach placers has been derived from altered, potash-deficient pelitic sediments of the Yellowknife group lying between the sillimanite and almandite isograds (Turner and Verhoogen, pp. 452–5, 468–9, 1951; Tilley, 1937), rather than from eclogites, which are not known to be present in the map-area. Tilley (1935) and Harker (1954) note kyanite replacing andalusite and cordierite metacrysts in the pelitic hornfelses of Ross-shire, northwest Highlands, and attribute the replacement to a regional metamorphism superimposed on the earlier thermal metamorphism of the area. This interpretation might be applicable to certain of the metamorphosed pelitic rocks of the Lac de Gras map-area.

Magnetite is an abundant mineral in the Yamba Lake sand (40 per cent), and only a minor constituent (3 per cent) of the garnet-rich sands of Exeter Lake. These differences are attributed to the types of rocks contributing to the two parts of the esker; the western granodiorites frequently have magnetite as an accessory mineral, magnetite is absent in the muscovite granites of the eastern part of the map-area. The magnetite is in unaltered, angular grains which in some instances show octahedral crystal faces.

Monazite comprises 1 per cent of the Yamba Lake sample, and makes this sand appreciably radioactive; the mineral is almost absent from the sands of Exeter Lake. This clearly implies local derivation of monazite. Monazite was separated in appreciable quantities from the biotite-rich phase of the Yamba Lake migmatites; recoveries indicate that parts of the rock contain 0.01 per cent monazite. Since the migmatites are an important

rock type in the area, it is likely that they were major contributors to the esker sands of Yamba Lake; it follows that most of the monazite found in the beach placer was probably derived by disintegration of the gneissic migmatite. Monazite is a rare accessory in the granites of the map-area, though a few grains were recovered in separations of muscovite-apatite granites (Plate I).

Monazite in the migmatite occurs as tabular crystals, 0.1 to 0.25 millimeters in diameter (fine sand size); the granular nature of the biotite-rich gneiss, together with this grain size, make the monazite separation and concentration by glacial disintegration, fluvio-glacial sorting, and wave winnowing, a relatively efficient process. The monazite in the beach placers has the same habit, range of grain size, and properties as the monazite in the migmatite. They are low specific gravity monazites (4.91 to 4.94 ± 0.05), with very low refractive indices—alpha 1.776, gamma 1.826 ± 0.003. Optically the most nearly comparable monazites are some from New Zealand and California, reported by Hutton (1950, 1952), though specific gravities of Hutton's monazites are higher (5.21 to 5.26). Unit cell size is normal; Professor Pabst of the University of California reports the following cell dimensions:

a_0 6.76Å, b_0 6.96Å, c_0 6.46Å, beta 103°50′10″; $a_0 : b_0 : c_0$:: 0.971 : 1 : 0.928

Spectrochemical analysis of the monazite (Table I), though only roughly quantitative, confirms the low thorium content suggested by index and density; with 1.0 per cent silicon rather more than 1.5 per cent thorium

TABLE I

SPECTROCHEMICAL ANALYSIS OF YAMBA LAKE MONAZITE

G. M. Gordon, Spectrographer	
Thorium	1.5%
Lead	0.4%±0.1
Phosphorus	Principal constituent
Silicon	1.0%
Iron	<0.1%
Aluminum	<0.1%
Zirconium	<0.1%
Magnesium	<0.1%
Calcium	<0.1%
Rare earth elements, based on estimates from line intensities without the aid of standards	
Large quantities	Nd, La
Medium quantities	Ce, Pr, Sm, Y
Small quantities	Dy
Questionable (low or medium or trace)	Yb, Er
Not detected	Eu, Gd, Ho, Lu, Tb, Tm

would be expected (Hutton, 1952). The rare earth content is comparable with that of monazites analysed by Murata, Rose and Carron (1953).

Monazite is concentrated in the finer screen-size fractions; there is 1 per cent monazite in the 60-65 mesh fraction (0.25 to 0.21 mm.) of the beach placer, 6 per cent monazite in the 100 to 120 mesh fraction (0.15 to 0.125 mm.); similar concentrations were noted in the heavy separations of the Yamba Lake migmatite. The grain size distribution appears to be a reflection of original crystal size, for many of the grains are idiomorphic, and few appear to be crystal fragments (Plate I).

Olivine is a rare constituent of the placers, and is concentrated in the moderately magnetic fraction of the sands, along with monazite. Olivine occurs in certain of the Proterozoic diabase and gabbro dykes of the map-area, and this may be the source of the olivine grains noted in the beach placers.

Pyroxene Group. Orthorhombic pyroxenes (hypersthene and enstatite) and monoclinic pyroxenes (augites) occur in small amounts in the beach placers, particularly those from Exeter Lake. Augite is an important constituent of the diabase and gabbro dykes of the area; Lord and Barnes (1953) have noted a stock-like pyroxenite intrusion into Yellowknife group sediments in the Aylmer Lake map-area to the east. Enstatite has been observed in migmatites similar to the Yamba Lake migmatite elsewhere in the Yellowknife geologic province; occurring in a granulite-facies rock consisting of quartz, almandite garnet, and enstatite interbanded with rocks of the amphibolite facies (Folinsbee, 1941). Hypersthene in the beach placers is readily recognized by its distinct pleochroism, and the suggestion is that hypersthene granulites must be present in the map-area to contribute this mineral to the beach placers. Conditions of metamorphism in the migmatites may approach those under which charnockitic rocks are developed (A. F. Wilson, 1947).

Rutile. A few pleochroic deep-red to reddish-brown striated angular crystals of rutile are present, and readily recognizable, in the non-magnetic fraction of the beach placers. They probably were originally accessory minerals in some of the granitic rocks of the map-area; rutile has also been noted as an accessory in the migmatites south of Yamba Lake.

Scheelite, in small quantities, was recovered from the non-magnetic fraction of the Yamba Lake concentrate; it is essentially absent in Exeter Lake concentrates. Under the ultraviolet lamp (2537 Å) the scheelite fluoresces a cold blue-white, indicating it is the tungsten-rich member of the scheelite-powellite series, as most scheelites in the Archean rocks of Canada appear to be. Index determinations (alpha 1.91, epsilon 1.93 $\pm$ 0.05) confirm the diagnosis. Scheelite occurs in the gold veins of the southern part of the Lac de Gras map-area, and, indeed, is widely distributed in small quantities through gold bearing veins of the Yellowknife geologic province (Lord, 1951). Since scheelite has good placering properties (gravity 6.0) over short distances (its cleavage and softness render it susceptible to attrition),

and is readily recognized with short-wave ultraviolet light, it probably is of value as a mineralization indicator. Presence of scheelite in the Yamba Lake concentrates suggests the presence of scheelite-bearing veins in the sediments southwest of Exeter Lake, an area not easily prospected because of heavy drift cover.

Sillimanite is fairly abundant in the non-magnetic fraction of the beach placers. It occurs in two habits: as fine radiating fibres in a cordierite or biotite matrix, and as rather coarse, elongate, single crystals. Sillimanite occurs in the most highly metamorphosed pelitic schists of the Yellowknife group metasediments, and as a patchily distributed accessory in the Yamba Lake migmatites.

Staurolite is a fairly abundant to minor constituent of the moderately magnetic fraction of the heavy sands, particularly those from Exeter Lake. It exhibits a sieve structure due to numerous inclusions, mostly of quartz, and has a distinct light to deep golden brown pleochroism. Crystal faces are present on a number of the detrital grains suggesting a fairly fine-grained staurolite schist source rock (Plate I). Staurolite develops in the moderately high grade pelitic schists of the Yellowknife group under certain rather special conditions; it is often found where the schists are caught up in granite re-entrants, as east of Exeter Lake. Turner and Verhoogen (1951, pp. 418, 419) suggest that staurolite is confined to rocks of high iron content, and that this chemical dependence accounts for its patchy distribution in pelitic schists of the kyanite subfacies.

Tourmaline grains, pleochroic light-brown to black, are a minor constituent of the moderately magnetic fraction of the beach placers. Many of the grains show prismatic and rhombohedral crystal faces, and are comparable in size and colour to tourmaline crystals developed by boron metasomatism in the pelitic Yellowknife group rocks, particularly in the thermal aureoles found around the muscovite granite. The muscovite granite and related pegmatites commonly have black tourmaline as an accessory mineral.

Zircon. Many types of zircon are present in the finer screen-size non-magnetic fractions of the beach placers; clear zircons, malacons, hyacinths, hyacinth cored, zoned, coloured, fluorescent and non-fluorescent varieties have been noted. Hyacinth has been cited as an Archean type zircon, confined to the ancient gneisses and related granities (Mackie, 1925; Tyler, Marsden, Grout, and Thiel, 1940; Bruce and Jewitt, 1936; Tomita, 1954). Wilson (1954) suggests that age-dating confirms Leith's concept (Leith, 1935) that the terms Archean and Proterozoic should be used for "types of rock, not time," since he and his co-workers find some belts of Archean-type gneisses to be much younger than Proterozoic-type rocks of other parts of the Precambrian shield. Hutton (1950, 1952) points out the ubiquitous distribution of hyacinth, which appears to support Wilson's suggestion that Archean-type gneisses are not confined to the Archeozoic.

Certain facts about the zircons of the map-area have been established. The zircons in the sedimentary phase of the injection gneiss south of Yamba

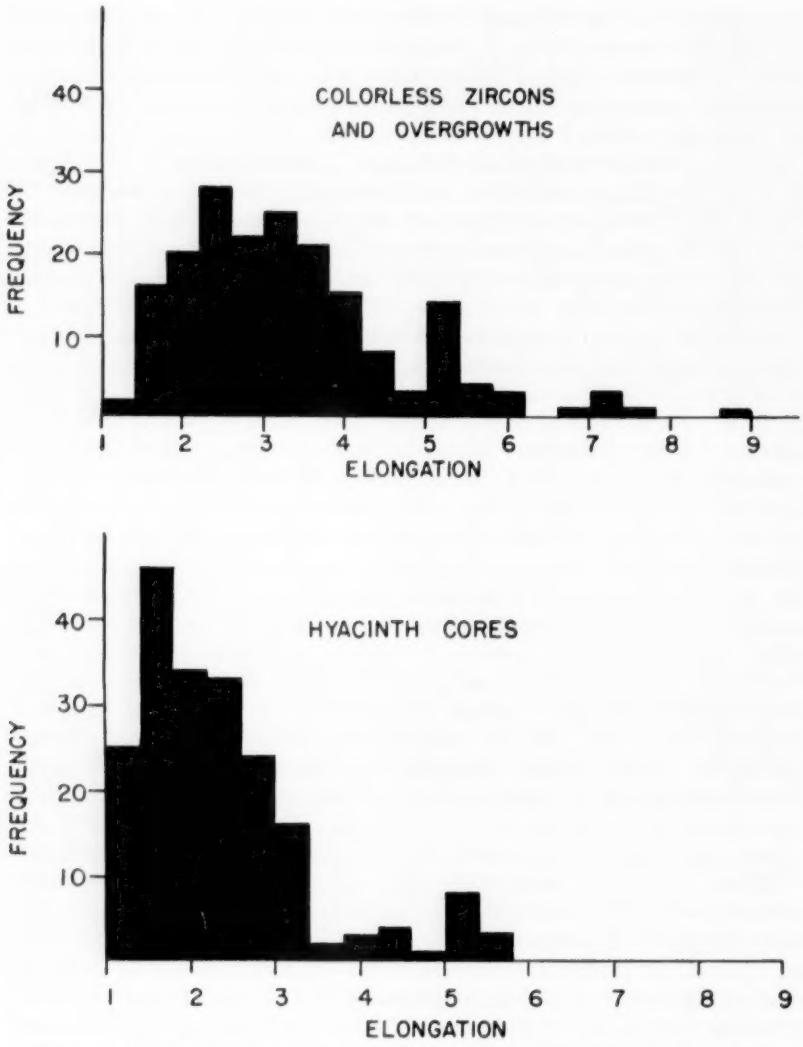

FIGURE 5.—Elongation frequencies of zircons from migmatite, Yamba Lake, Lac de Gras map-area.

Lake are invariably hyacinth cored, in most cases with light-coloured overgrowths, perhaps of malacon (Plate I). The zircon in the early granitic intrusives (the hornblende-biotite diorites) is an extremely elongate, comparatively large, uniformly coloured hyacinth variety. Zircons are rare in the muscovite-apatite granite, those present are of "normal" type—elongate, clear, high index, strongly birefringent, and sharp-angled. Zircons

from the igneous phase of the migmatite are elongate, colourless, zoned, and neither as abundant or large as those from the biotite-rich sedimentary phase. Large zoned zircons are common in the beach placers, their source is probably the granites intruding the migmatites.

If the conclusions of Tyler, Marsden, Grout, and Thiel for the Lake Superior region were applied to the zircons of the Lac de Gras map-area, one would classify the migmatitic paragneiss as an Archean rock, intimately injected by later Archean granites responsible for the malacon overgrowths. The muscovite-granite would be of Killarnean type. This is in general agreement with field observations, but age dating suggests that the time interval between the earliest hornblende diorites and the latest muscovite pegmatites is small, and that the intrusions were probably confined to a single short-lived Archean orogeny.

Zircon of the hyacinth variety, separated from the injection gneiss or migmatite, is non-fluorescent. The normal type zircon, separated from the muscovite-apatite granite, fluoresces a pale golden yellow in short wave ultraviolet light. The muscovite granite is clearly a magmatic type. These observations on fluorescence phenomena are in agreement with those of Foster (1948) for certain zircons from North American granites and those of A. F. Wilson (1950) for the zircons of granites and related gneisses of Central Australia.

The hyacinth-cored zircons show elongation frequencies resembling those reported by Wyatt (1954) for the Moine granulites. Elongation of the hyacinth core is even less than the elongation of the zircon with overgrowths (Figure 5); however, it is the writer's opinion that the roundness of the hyacinth-cored zircons may be in part a function of their rotation during formation of the granulitic migmatite, rather than an entirely inherited sedimentary or aeolian effect, as suggested by Wyatt. Zircons from the Yellowknife hornblende-biotite diorite (K.A. 23–30, Table II) resemble the hyacinth in the migmatite except in elongation. Hyacinth needles in the diorite have elongation indices approaching 32.0, a figure which Poldervaart (1955) notes for zircons from a similar early marginal phase of a granitic pluton. Zircons were insufficient in number in the muscovite granite to provide for a statistical study, but average elongations were of the order of 3, further confirming the magmatic character of this intrusive. In respect to zircon elongations and habits, as well as in the presence of abundant apatite and tourmaline, the muscovite granite resembles the Leinster granite of the north of Ireland as described by Smithson (1932).

Age Dating

Until recently very little was known as to the ages of the rocks in the Yellowknife geologic province; the apparent absence of uraninites has been a bar to application of the accepted uranium-lead methods of age dating. One potassium-argon age has been reported (Shillibeer and Russell, 1954), a determination on perthite from the Moose dyke pegmatite, 2150 million

TABLE II

POTASSIUM-ARGON AGE DATA, YELLOWKNIFE CONTINENTAL NUCLEUS, N.W.T.

Number	Location, latitude & longitude	Type of specimen	A^{40}/K^{40}	Ages using alternative decay constants	
				λ 0.547 R: 0.089*	λ 0.558 R: 0.110**
				m.y.	m.y.
K.A.12	Prosperous Lake map-area 62°40′N, 114°10′W	Muscovite-biotite granite	0.195	*2230*	1950
K.A.31	Walmsley Lake map-area 63°56′N, 108°40′W	Biotite from muscovite-biotite granite	0.266	2650	*2340*
K.A.23	Yellowknife Bay map-area 62°19′N, 114°15′W	Plagioclase from hornblende-biotite-diorite	0.080	1250	1060
K.A.30	Same specimen as K.A.23	Biotite and hornblende from diorite	0.264	2640	*2330*
K.A.33	Courageous Lake map-area 64°16′N, 111°27′W	Quartz and feldspar from rhyolite porphyry	0.162	*2000*	1740
K.A.21	Yellowknife Bay map-area 62°30′N, 114°20′W	Albite from granite boulder in Yellowknife group sediments	0.098	1441	1232
K.A.24	Lac de Gras map-area 64°48′N, 111°41′W	Feldspar and muscovite from injection gneiss	0.118	1634	1405
Tor. 1069A***	Beaulieu River map-area 62°11′N, 112°12′W	Perthite from Moose dyke pegmatite	0.186	*2150*	

*Branching ratio which equates argon ages of potash feldspars with U-Pb age of uraninites from related pegmatites, after Shillibeer and Russell (1954). Wasserburg and Hayden (1955) found applicable almost the same decay constants (λ0.55 and R: 0.085).

**Branching ration given by averaging results of 8 gamma-ray counting experiments reported in the literature is 0.110±0.012.

***Shillibeer and Russell (1954). All other values are those determined by Folinsbee, Lipson, and Reynolds (1955).

years (Table II). This pegmatite is thought to be comparable in age to pegmatitic phases of the muscovite granite of the Lac de Gras map-area. It was pointed out by Shillibeer and Russell that this potassium-argon age is confirmed by the average of 8 galena ages for the Yellowknife geologic province, 2160 million years (Russell, Farquhar, Cumming and Wilson, 1954), though this average galena age has since been increased to 2255 m.y. using a later modification of the galena age equations (Russell and Cumming, 1955). Galenas from gold-bearing quartz-tourmaline veins,

apparently related to the muscovite granite (K.A. 12, Table II), returned ages of 2365, 2340 and 2280 m.y., using the modified age equations. The galena from Horseshoe Island, near the hornblende biotite diorite, returns an age of 2255 m.y. The hornblende-biotite diorite is a marginal phase of the intrusive which returned a young false age when dated by the helium method (Keevil, Jolliffe and Larsen, 1943).

Seven potassium-argon age determinations on rocks and minerals from the Yellowknife continental nucleus have been made at the University of California, Berkeley, using the extremely sensitive apparatus assembled by J. H. Reynolds and J. Lipson, of the Department of Physics (Folinsbee, Lipson, and Reynolds, 1955). J. H. Reynolds made all the spectrometric measurements here reported, J. Lipson did the tedious and exacting argon separations, while the writer made the mineral separations and potassium analyses. All samples used were collected in the field by the writer.

The italicized values are believed to be closest to the true age of the granitic intrusives of the Yellowknife geologic province, and the two determinations on biotite are absolute age determinations in that they are calculated from experimentally determined decay constants. The anomalies are similar to those recently reported by investigators at the Carnegie Institution, Washington (Aldrich, Davis, Tilton, and Wetherill, 1955) and will not be discussed in this paper.

Zircon was separated from the hornblende-biotite diorite (K.A. 23, 30) and a sample forwarded to the United States Geological Survey for a lead-alpha activity age (Larsen, Keevil, and Harrison, 1952). Dr. Gottfried reports an alpha activity of 161 alphas/milligram/hour, a lead content of 69 ppm. and an age of 904 m.y., an anomalously low figure which is, however, in fairly good agreement with the potassium-argon age of the plagioclase fraction of the same rock (K.A. 23, Table II). A cross check on the zircon age was made by the writer using the method suggested by Hurley and Fairbairn (1953) and extended by Holland (1954).

The density of the sample submitted to Gottfried was established as 4.40 ± 0.02, using a Berman balance. From Holland's table this indicates a radiation dosage of 410×10^{13} alphas/milligram. Selected large crystals of zircon, for which the whole crystal emission was believed to be insignificant, gave a broad but symmetrical peak at 2θ 35.31 indicating a radiation dosage of 400×10^{13} alphas/milligram. Small single crystals were measured by Pabst and Quaide, and, probably due to significant whole crystal emission of alpha particles, indicated much smaller radiation dosages. Using Holland's expression for the age, and a 405×10^{13} alphas/milligram average radiation dosage figure, the age of the zircon is 2380 m.y., with a rather high probable error.

Monazite from the Yamba Lake migmatite, thought to be introduced at the time of intrusion of the muscovite-biotite granites, has an alpha activity of 4165 alphas/milligram/hour (Gottfried, personal communication). Gordon (Table I) reports a lead content of 0.4 per cent, $\pm$ 0.1, using

spectrochemical methods. The monazite is roughly 2000 m.y. old, using this data; a chemical analysis for lead by the U.S.G.S. suggests the monazite age to be 2780 m.y. (4035 alphas/milligram/hour, 6190 ppm. Pb), a figure to be used with caution (Stieff and Stern, personal communication).

Both the monazite and zircon appear to be minerals for which a more precise age determination could be made using the lead isotope methods of Holmes (1954) for monazites, and the group from the Carnegie Institution (Aldrich *et al.*, 1955), for zircons.

The most important single conclusion that can be drawn from this data at the present time is that there appears to be no significant age difference between the "older" hornblende biotite diorites (2330 m.y.) and the "younger" muscovite granites (2340 m.y.). These figures are believed to be very close to the actual age of the major period of granitic intrusion in the Yellowknife continental nucleus.

Summary and Conclusions

The esker sands of the Lac de Gras map-area represent the disintegrated, sand-size derivatives of rocks of the Yellowknife group and later granitic intrusives. The two heavy concentrates are typical of those formed, respectively, on granitic and metamorphic terrains; they are indicative of the probable contribution of this portion of the Precambrian shield to later geosynclines. They also afford basic data as to the Precambrian contribution to the glacial deposits of western Canada. In these respects the study may be of interest to sedimentary and glacial geologists working on the western plains.

The marked localization of the esker source material is significant. Wilson (1939) put forward some speculations on this matter, unsupported by field evidence, and these are supported by the present study. The very limited distribution of the monazite-bearing sands is of especial significance. The monazite appears to have been derived almost entirely from a migmatite rich in the radioactive minerals zircon and monazite. No commercial concentrations of radioactive minerals have been reported from rocks of the Yellowknife geologic province, whereas important uranium ore-bodies are located in the adjoining, later, Great Bear and Churchill orogenic provinces. The thorium content of the Yamba Lake migmatite makes this area an immense low grade concentration of radioactive material, which, lying at the root of the Archean mountains, was not subjected to effective concentrating mechanism during the major orogeny.

Age dating suggests that in the Yellowknife geologic province we have a single short-lived series of Archean granite intrusions, which crystallized about 2340 million years ago, and which beautifully illustrate the granite series as developed by Read (1947) and others. It seems likely that the intrusives of the Yellowknife continental nucleus were contemporaneous with the granitic intrusions of the Superior or Keewatin nucleus; a correlation of these two nuclei is indicated.

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SECTION FOUR

Precambrian Nomenclature in Canada

J. E. GILL, F.R.S.C.

ABSTRACT

In the interest of clarity and better understanding between workers in different fields it is recommended (1) that the rock-stratigraphic terms, "group," "formation," "member," and "bed" be used in describing Precambrian formations, following the definitions given by the American Commission on Stratigraphic Nomenclature—there is, at present, no good reason for using time-stratigraphic terms; (2) that the names Keewatin, Timiskaming, Huronian, Keweenawan, Grenville, Laurentian, Algoman, Matachewan, and Killarnian be avoided in describing Precambrian rocks, except in the type localities; (3) that Archaean and Proterozoic be dropped or else used exclusively in a time sense. Actually they are not needed. Early Precambrian and Late Precambrian are sufficient as time terms for the present, but should only be used where there is some good evidence of absolute age.

NAMES, if well defined and carefully used, are a great help in communicating ideas. If used in different senses by different people they can be a great source of confusion; in the extreme they can be a real barrier to clear thinking. The extreme case is, I think, well illustrated by certain names widely used in describing Precambrian formations, as I have tried to point out in earlier papers (Gill, 1955). In this one I intend to discuss some of these names more fully and to suggest changes in the hope that those fellows of Section IV who supervise government and other publications or who conduct university courses will consider them and perhaps be induced to act in the ways suggested or in other ways to clear up the confusion.

The names to be dealt with here fall naturally into three groups: first, the terms widely used for description of stratified rocks regardless of age or locale; second, names applied originally to particular rock groups and since extended to other groups because of similarity of composition, structure, and sequential relations; third, time terms that have, through false reasoning, come to imply certain rock assemblages.

Terms of the first group have been systematized by stratigraphers dealing with fossiliferous series. While there is some argument about details, two sets are in general use. Rock-stratigraphic divisions are based on rock units as seen in individual stratigraphic sections. From larger to smaller units they are: group, formation, member, bed. Time-stratigraphic terms are based mainly on the best determinations of age that can be made from the study of fossils or by other means. They are: system, series, stage, and zone. Since we have at present no means of dating Precambrian rocks closely, it would be better if only rock-stratigraphic terms were used in describing

them. This has not been the practice in the past, but more detailed stratigraphy is now being done in the Precambrian and a change to this system should assist us in keeping our ideas straight. It would also clear the decks for proper application of time terms, if and when improved dating methods justify their use and should assist us in getting expert stratigraphers to take an interest in Precambrian problems.

The second group includes Keewatin, Temiskaming, Grenville, Huronian, Keweenawan, Laurentian, Algoman, Killarnian. Each of these was introduced originally to describe a particular rock assemblage. Through subsequent use, with the best of intentions but based on false premises, these have been applied to various rock groups in widely separated areas. It is my impression that they now have the following meanings in the minds of most Canadian geologists.

Keewatin—a folded volcanic assemblage more or less metamorphosed, possibly with some interlayered sediments; applied only if the rocks are known to be or are believed to be the oldest rocks in the area; probably formed in the early part of the Early Precambrian.

Temiskaming—folded and more or less metamorphosed greywacke with more or less argillite, siltstone, conglomerate, iron formation or volcanics known to rest or believed to rest conformably or uncomformably on a volcanic assemblage (Keewatin) or unconformably beneath a Huronian assemblage (described below); probably formed in the later part of the Early Precambrian.

Huronian—flat-lying, gently folded or locally closely folded, well-sorted sediments, mainly limestone, quartzite, argillite, and conglomerate with more or less greywacke, iron formation, and volcanics; generally rests unconformably on assemblages of greywacke and volcanics or intrusives; probably formed in the early part of the Late Precambrian.

Keweenawan—flat-lying or mildly deformed sandstone, conglomerate, and shale with more or less volcanics; probably formed in the later part of the Late Precambrian.

Laurentian—pre-Timiskaming granite.

Algoman—post-Timiskaming and pre-Huronian granite and associated intrusives.

Killarnian—Late Precambrian granite.

The correlation implied by use of any one of the names listed above to describe rock bodies or assemblages widely separated in space and without traceable connections resulted from erroneous ideas, based on limited knowledge. The Precambrian was thought to have encompassed only two or three world-wide revolutions in a period of time much shorter than the two billion or more years now assigned to it. The rapid increase of knowledge of earth processes and the time involved now makes it clear that instead we must visualize many deformations at different times, each affecting a limited belt.

Precambrian rock groups differ little from younger ones, except for the lack of fossils. There is a higher proportion of metamorphic types in the Precambrian, it is true, but this can be accounted for by deeper erosion in most areas where Precambrian rocks are exposed. Any particular Precambrian assemblage can be matched fairly closely in younger series. It is also possible to find sequences in younger series similar to those in the Precambrian, with folded volcanics and greywacke covered unconformably by limestone-quartzite-argillite series, the whole cut by diabase dykes. This being so, one cannot be sure that any particular rock type or combination of rock types formed only during a particular period in the Precambrian. It is not, therefore, good science to continue using names that imply that they did.

Realizing that there is no real basis for the correlations implied by use of the names in question, some authors have, in recent years, used "Keewatin-type" and "Timiskaming-type" in tables of formations and in rock descriptions. These labels really add nothing but confusion to a table of formations. A short description of the rock types is given in such tables and the relative ages of the different groups is shown. All that Keewatin and Timiskaming or Keewatin-type and Timiskaming-type add is a suggestion of rough equivalence in age to the original Keewatin or Timiskaming for which there is, ordinarily, no basis whatever. In writing about the rocks in more general vein, "the older volcanics," "the folded metavolcanics," or the "basalt-greywacke assemblage" are more specific and little, if any, longer than "Keewatin-type assemblage" or "Timiskaming-type assemblage." It appears, therefore, that something would be gained if these names were not used, except in reference to the rocks in the type localities.

Many geologists now recognize that sedimentary groups labelled "Huronian" are similar lithologically but are not necessarily of the same age. At the same time, they assume that such rocks are Late Precambrian in age. These assemblages are now recognized by stratigraphers as sediments characteristically formed in marginal or epicontinental seas, or possibly in miogeosynclines, where waves and currents have had an opportunity to do a better-than-average job of sorting. Nobody has shown so far that this could not have happened in the Early Precambrian as well as in the Late Precambrian. "Huronian-type sediments" carries implications of age and correlation that will stick in spite of attempts to redefine it, but if a short, compact designation is needed, "shelf-type sediments" is preferred.

"Grenville-type" assemblages are mostly highly metamorphosed shelf-type sediments and might better be so designated since "Grenville-type" carries implications about age, though different people may have different ideas of the age.

Keweenawan may be reasonably applied to sediments or volcanics conformably or disconformably underlying Lower Cambrian sediments, though they may differ considerably in age from the original Keweenawan. That sediments previously thought to be Keweenawan may be much older has

recently been indicated by age determinations on pitchblende from veins cutting the Athabaska sandstone (Collins *et al.*, 1952). Diabase dykes formerly classed as Keweenawan may be of diverse ages. Such dykes are formed as late stage injections in many mountain-built belts. Possibly, therefore, some may be of Early Precambrian age. The use of Keweenawan or Keweenawan-type in describing these is not necessary and may be misleading. "Matachewan" may also be misleading in its general application.

Batholithic intrusives rise mainly in the late stages of orogenesis. If there were many episodes of orogenesis, so too there should have been many batholithic groups of different ages. The widespread use of Algoman for batholithic masses cutting folded volcanics or greywacke assemblages should definitely be stopped. Laurentian has already been almost dropped and there seems to be no reason to revive it. Killarnian is relatively new and has not been widely used. It should be applied only in the type area.

It now appears possible to date approximately many of the batholiths by radioactivity methods. After a large number of determinations have been made, we may be able to trace out mountain-built belts, which should then be named. Until this is possible, names other than "batholithic intrusives," "granite batholith" and the like, can serve no useful purpose.

The third group of confusing terms includes Archaean—spelled Archean in the United States, Archaen in some other parts of the world—and Proterozoic.

Archaean was used at an early stage as equivalent to "pre-Cambrian." In recent years it has been used in Canada as equivalent to Early Precambrian but unfortunately, it has also come to imply certain rock types embracing the Keewatin and Timiskaming assemblages as defined above, with various igneous masses intrusive into them. In some instances in Canada, and commonly elsewhere, high grade metamorphics including metamorphosed shelf-type sediments marked by quartzites and crystalline limestones, have been classed as Archaean, but unmetamorphosed or moderately metamorphosed shelf-type sediments are never so classified. Since all will agree that metamorphism of sediments to gneisses, quartzite, and marble was not exclusively an Early Precambrian process, this classication does not make much sense.

C. K. Leith, in 1933, noting that implications of time equivalence inherent in the use of Archaean and Algonkian, applied to rock groups were not, in most instances, justified, recommended that Archaean should be used only in reference to "the underlying, more or less indivisible, basement complex, containing igneous or sedimentary rocks, or both, in which ordinary stratigraphic methods do not apply." This recommendation has not been followed in Canada. The only reasonable way out of the dilemma is to drop Archaean completely. Actually it is not needed. Where radioactivity dating shows great age, Early Precambrian is sufficient. Where no information about absolute age is available relative age may be indicated by ex-

pressions like "basal gneiss," "older lavas," group 1 (as contrasted with 2, 3 etc.) or by local names. "Basement complex" or "basal complex" may also be useful on occasion.

Proterozoic has been used as a time term, equivalent to Late Precambrian. Flat-lying or mildly deformed Precambrian groups resting unconformably on older rocks have commonly been referred to as Proterozoic. This implies knowledge of absolute age where in most cases none exists. If there is no reliable evidence of absolute age, the name Proterozoic should not be used.

In conclusion, I wish to say that the recommendations for revision given above have been advanced mainly as a result of experience in graduate seminars on the Precambrian during the past three years. Students take the names and implied correlations found in official publications very seriously and it is difficult to get them to think and write objectively about Precambrian history, or even about some aspects of their field problems, when the current literature is full of the names discussed in groups 2 and 3. Let us face the facts and clear away the underbrush for the next generation! The older literature cannot be changed, but dropping the misleading words from current publications will effect an immediate improvement.

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SECTION FOUR

Carbon-14 Age Determinations at the University of Saskatchewan

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ABSTRACT

The original Libby technique has been used to determine ages of materials at the University of Saskatchewan. Some of the limitations and difficulties which were encountered are discussed. A list of some radiocarbon dates on a number of the materials which were investigated is appended.

Introduction

CARBON-14 age determinations have been made at the University of Saskatchewan, using the original Libby technique of counting solid carbon samples in a screen-wall counter (Libby, 1952). Certain limitations and disadvantages have made themselves evident. The most serious of these is radioactive contamination of the prepared samples probably due to radioactive fall-out following nuclear weapons tests. Only during periods when no such tests were being made was it possible to obtain satisfactory results.

Other more minor difficulties have arisen at different stages in the procedure of sample preparation and radioactivity determination. The steps in the procedure will be outlined, and the limitations and difficulties arising in each step are considered below.

Limitations of the Method, and Difficulties Encountered

1. The sample, as received, must be given a preliminary treatment to remove materials containing carbon of an age other than that which is to be determined. In many cases, this involves the removal of modern roots from the sample. This is usually done by hand under a magnifying glass, and is a very tedious and time-consuming operation, particularly where large amounts of sample are required, as with the Libby technique. The majority of the samples received require such treatment, and in unfavourable cases, eight or twelve hours of work may be involved. This step would be necessary with any method of carbon-14 age determination, but techniques utilizing smaller samples, for instance the acetylene method (Suess, 1954), require correspondingly less time.

There is a need for the development of new techniques for this separation process, or else this may become the limiting factor in extending age determinations to still older periods. It will probably be very difficult in the general case to be sure that the extent of contamination of an old sample with modern carbon is not greater than 0.1 per cent. The activity due to

this small proportion of modern carbon would, by itself, lead to an apparent age of about 50,000 years in a sample which was actually much older. Any method which attempts to be applicable to old material, therefore, is dependent upon a satisfactory preliminary treatment of the sample.

Removal of contemporary carbon in the form of carbonates from an organic sample is readily accomplished by treatment with acid.

2. The carbon contained in the sample must be converted to carbon dioxide gas. For organic material, combustion in oxygen is used, while carbonate materials, such as shells, are treated with acid. The carbon dioxide gas so prepared is purified by physical and chemical methods. It seems probable that this step will be used in all counting techniques.

3. The purified carbon dioxide is converted to solid carbon by passing the gas over molten magnesium metal in an iron tube. The reduction normally goes quite smoothly and efficiently and yields are nearly quantitative. This ensures that any isotope effect will be small. The products of the reaction are carbon and magnesium oxide, along with some unreacted fused magnesium metal. They are usually present in a hard compact mass which is very difficult to remove from the iron tube.

The separation of the carbon from the magnesium oxide is not as straightforward as it might appear. Treatment with hydrochloric acid leaves a solid residue containing about 10 per cent MgO. A subsequent treatment with nitric acid serves to oxidize part of the carbon which was forming a protective coating over the oxide, and reduces the percentage of MgO to about 0.5 per cent.

It has been our experience that the product recovered from this treatment, even after thorough washing with water, is not always satisfactory for counting purposes. Gases, presumably oxides of nitrogen, are released when the sample is placed in the screen-wall counter and interfere with the counting process. A further treatment with hydrochloric acid, followed by washing with water, always produced a product which was satisfactory from this viewpoint.

4. The solid carbon from the acid treatments is dried and ground in a clean mortar. It is then made into a thin paste with a dilute agar solution and coated in a uniform layer on the inside of a stainless steel cylinder. This is then partially dried in a stream of warm air, and placed inside the screen-wall counter.

It is in the grinding and coating procedure that the risk of radioactive contamination appears to enter most seriously. Particles of radioactive dust in the air have interfered very seriously with this step and have been the source of irritating and frustrating difficulties. Of all the limitations of the solid carbon technique this is considered to be the most serious by far. Carbon prepared from anthracite coals should be inactive, and when measurements are made on this material, contamination is shown by the appearance of an activity above the background value.

It is necessary to bracket each measurement on an unknown sample with

measurements on coal. If the radioactivity of the coal samples is effectively zero, this gives some assurance that the intervening measurement on the unknown sample was not in error due to contamination. It is to be noted that such contamination will yield an age value which is too small.

5. After the moist carbon on the cylinder is placed in the screen-wall counter, it is necessary to evacuate continuously for a period of at least twenty-four hours to remove most of the water from the carbon. The presence of water vapour in the counter affects the counting rate adversely. The counter is then filled with the counting gas mixture of argon and ethylene and the radioactive measurements are made. The screen-wall counter and the anti-coincidence circuits, which were obtained from the Atomic Instrument Company, Cambridge, Mass., have proved to be, in the main, quite reliable. Only occasionally have electronic faults been observed, and they are usually immediately shown by a variation in the background counting rate which is normally constant at 3.75 ± 0.10 counts per minute. Occasional trouble has resulted due to particles of carbon falling off the coating on the cylinder. This leads to an increased counting rate due to spurious pulses. These can be recognized by their abnormal appearance on a monitoring oscilloscope.

6. After a counting period of approximately 48 hours spent in the measurement of background and sample counting rates, the sample is removed from the cylinder and analysed for per cent carbon. This is usually around 90 per cent, the remaining 10 per cent being mostly water with a small amount of ash. The water is very firmly held by the carbon and is not removed during the prolonged evacuation period. Corrections must be made in each case for the observed per cent of carbon in the sample.

The Libby method has inherent limitations in age range and in precision, both of which are due to the low efficiency (5 per cent) of counting weak beta rays from solid samples because of self-absorption effects. The chemical preparation of the solid carbon for counting by the Libby method requires a somewhat involved and tedious procedure. Compounds which can be prepared for counting by a more direct and rapid method as in the methanol or acetylene synthesis, offer distinct advantages.

The solid carbon method requires approximately 10 grams of carbon for an age determination. Due to the small amount of some samples which are available, this is a stringent limitation.

However, in our experience, the most serious limitation of the Libby method is the possibility of contamination by radioactive dust which is involved when the purified sample is exposed to the atmosphere. The synthesis of compounds which can be purified and transferred in the gas phase permits a system in which the possibility of contamination due to radioactive dust is almost negligible. To attain adequate sensitivity, proportional counting and scintillation counting techniques may be used. The former was first developed in a workable form at the United States Geological Survey in Washington, while the latter is under investigation at the Universities

TABLE I

RADIO CARBON DATES

Sample number	Origin of sample	Age (years)
S–1	*Labrador:* Wood from bank of Crooked River, 50 miles northeast of Goose Bay, Labrador. Found under 10 feet of sand and clay. Submitted by W. Blake Jr. McGill University.	2110±245 2020±195 1610±217 Av. 1910±130
S–2	*Saskatchewan:* Bison bones taken from red ochre layer seven feet below surface at Mortlach Midden. Submitted by B. Wettlaufer, Archeologist, Province of Saskatchewan.	3400±200
S–3	*British Columbia:* Charcoal from Locarno Beach, Vancouver Island, 95 inches below surface. Submitted by C. E. Borden, University of British Columbia.	2430±160
S–4	*British Columbia:* Charred pine cones from bottom of hearth pit of circular lodge on north shore of Natalka Lake, Tweedsmuir Park. Submitted by C. E. Borden, University of British Columbia.	2415±160
S–7	*Ontario:* Interstadial calcareous gyttja from Lake Erie shore, nine miles north of Port Stanley, Ontario. Covered by 100 feet of Pleistocene deposits. Submitted by A. Dreimanis, University of Western Ontario.	older than 25,000
S–12	*Northwest Territories:* Shells from surface deposits near Coral Harbour, Southampton Island. Elevation 105 feet. Submitted by J. B. Bird, McGill University.	3670±270
S–13	*Northwest Territories:* Shells from side of a terrace of Matthiassen Brook, Southampton Island. Elevation 170 feet. Submitted by J. B. Bird, McGill University.	5600±300
S–17	*British Columbia:* Charcoal from Marpole site, collected at a depth of 55–65 ins. Submitted by C. E. Borden, University of British Columbia.	2015±166 1880±180 Av.1950±125
S–22	*Saskatchewan:* Bison bone from Mortlach Midden, three feet below surface. Submitted by B. Wettlaufer, Archeologist, Province of Saskatchewan.	1580±159
S–25	*Ontario:* Fragment of log from stratified gravel bed, 8 feet above level of Lake Huron, near Blackwell, Ontario. Submitted by A. Dreimanis, University of Western Ontario.	4400±216
S–26	*Ontario:* Peat from gravel pit, Amber, Ontario. Embedded in gravel at a depth of 65 feet. Submitted by A. Dreimanis, University of Western Ontario.	older than 23,000
S–28	*Saskatchewan:* Humus with fragments of charcoal four feet below surface at Mortlach Midden. Submitted by B. Wettlaufer, Archeologist, Province of Saskatchewan.	2400±173
S–31	*Ontario:* Driftwood from Lake Arkona gravel near Ridgetown, Ontario. Submitted by A. Dreimanis, University of Western Ontario.	12,850±634 12,470±603 Av.12,660±440

of Chicago and Manitoba. The electronic counting techniques are perhaps somewhat more involved than the Geiger counter method of Libby, but not enough to create a serious disadvantage. At the University of Sas-

katchewan, proportional gas counting methods are now being introduced.

Table I gives the results of age determinations made during periods when no difficulties due to radioactive fall-out were encountered. It is a pleasure to acknowledge the generous financial aid of the Saskatchewan Research Council and the technical assistance of Mrs. Maria Thomas.

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SECTION FOUR

Report of the Committee on Precambrian and Related Dating

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ABSTRACT

The report of the sub-committee on Precambrian and Related Dating is a brief review of recent developments in the field of geological age determination by the various uranium-lead, thorium-lead, potassium-argon, and rubidium-strontium age methods. It includes a table of recent published age determinations made on material from Canadian Precambrian areas.

Introduction

In the past, published age determinations on material from Canadian Precambrian areas have been included in the Annual Reports of the Committee on the Measurement of Geological Time, published by the National Research Council of the United States. It is thought that the present volume of work being done in Canada and on samples of Canadian rocks warrants the preparation of a report concerned solely with the problems of geological time as applied to Precambrian areas in this country.

The importance of this subject has already led to a symposium on Precambrian Correlation and Dating (Geological Association of Canada, 1955), and in turn to the formation of the sub-committee on Precambrian and Related Dating. The primary aim of this sub-committee is to acquaint Canadian geologists with developments in the field of geochronology, with specific reference to the Precambrian areas of Canada. It is also hoped that the sub-committee's findings will suggest how age determinations may be useful in solving geological problems, and clarify and define the limits of usefulness of age measurements.

Absolute determinations of the geological ages of rocks and minerals are based on the decay of five naturally occurring radioactive isotopes:

$$U^{238} \rightarrow Pb^{206}$$
$$U^{235} \rightarrow Pb^{207}$$
$$Th^{232} \rightarrow Pb^{208}$$
$$K^{40} \rightarrow A^{40}$$
$$Rb^{87} \rightarrow Sr^{87}$$

These isotopes have proved suitable for dating purposes because their half-lives are of the same order of magnitude as the length of geological time, and because their mode of occurrence in the earth's crust has made them amenable to study.

Absolute ages based on the decay of these isotopes are calculated from a measurement of the ratio of the parent radioactive isotope to the amount of stable daughter isotope which has accumulated in the rock or mineral since the time of deposition. Thus it is necessary to determine the ratios Pb^{206}/U^{238}, Pb^{207}/U^{235}, Pb^{208}/Th^{232}, Sr^{87}/Rb^{87}, and A^{40}/K^{40} in order to calculate age values. It is also possible to determine an age from the ratio radiogenic Pb^{207}/Pb^{206} in uranium minerals, but such a value is not independent of those calculated from the Pb^{206}/U^{238} and Pb^{207}/U^{235} ratios in the same mineral. A calculated age will represent the true age of a rock or mineral only if certain conditions have been fulfilled. There must have been no loss or gain of parent or daughter isotopes by leaching or redeposition during the sample's history. The amount of stable daughter isotope used in the calculation must be that amount which has accumulated since the deposition of the sample and must not include any originally present at the time of deposition. Finally, such absolute ages will only be as accurate as the measured values of the decay constants used in the calculations.

The Uranium and Thorium-Lead Methods

These methods, based on the decay of uranium and thorium to lead, have been investigated far more fully than the potassium-argon and rubidium-strontium methods. The decay constants of uranium-238 and uranium-235 have been determined with considerable accuracy. Ages based on the Pb^{208}/Th^{232} ratio are often lower than the corresponding Pb/U ages, and it has been suggested that a redetermination of the Th^{232} decay constant would be worthwhile.

In many of the age determinations made during the past fifteen years, it has been found that the ages calculated from the three uranium lead ratios in a given sample do not agree. Generally the Pb^{207}/Pb^{206} age is highest, the Pb^{206}/U^{238} age is lowest, and the Pb^{207}/U^{235} age is intermediate. Extremely discrepant age values following this pattern have been found for pitchblende samples from the Lake Athabasca region. In order to explain the discrepancies and the observed pattern of ages, it has been suggested that continual loss of radon-222, a gaseous intermediate member in the decay of uranium-238 to lead-206, has occurred. An alternative explanation is that lead has been lost by chemical leaching at some period in the history of the rock or mineral. Measurements of radon loss from Lake Athabasca pitchblende samples and other primary uraniferous minerals such as uraninites and samarskites suggest that losses of radon are less than 3 per cent, although secondary uranium minerals may be subject to losses as high as 20 per cent or more (Kulp *et al.*, 1954; Russell, unpublished results). Kulp *et al.* (1955) have recently concluded that radon loss is insufficient to explain the discrepancies found in the apparent ages of Lake Athabasca pitchblendes.

Recent investigations of both the mineralogy and the apparent ages of these pitchblendes have been made by members of the Geological Survey

of Canada and other groups. Their findings suggest that loss of lead has occurred from the pitchblendes during several periods of redeposition or reworking by hydrothermal solutions. The radiogenic Pb^{207}/Pb^{206} ratio is least sensitive to losses or gains of radiogenic lead during the geological history of a uranium sample, and the age calculated from this ratio should thus be closest to the true age of deposition.

A significant contribution to the field of geochronology has been the results of age determinations made by analyses of the microgram quantities of uranium, thorium, and lead in various fractions of a specimen of Essonville granite from the Tory-Hill district, Ontario (Tilton *et al.*, 1955). The age values obtained from the various fractions are included in Table I, and lie in the range of previously published ages for macroscopic samples of uraninites and other primary uranium minerals from Grenville pegmatites.

Numerous studies of the distribution of uranium and thorium in granitic rocks indicate that these elements are concentrated mainly in accessory minerals such as zircon and sphene (Faul, 1954). The alpha activity and the lead content of zircons separated from granites have been used to determine age values, and several zircon ages have been determined for the Essonville granite. These are also in good agreement with other Grenville age values. Thus the ages of the granite and the pegmatites agree.

From the results of all these studies it appears that fresh unaltered samples of primary uraninites, samarskites, and zircons generally give reliable ages which date the time of formation of the rock or pegmatite in which they are found. It should be stressed that both chemical and mass spectrometric analyses should be made in order to check the possibility of loss of lead, and to correct for the presence of original lead in the sample. Vein minerals, such as pitchblendes, are susceptible to leaching of lead, and at best can date only the time of emplacement of the sulphides with which they are associated. Secondary minerals such as carnotites do not give reliable age values because of high radon loss and the ease with which both losses of lead and uranium may occur.

The Galena Method

It is now well known that considerable variations exist in the relative abundances of the isotopes Pb^{204}, Pb^{206}, Pb^{207} and Pb^{208} in different lead ores and minerals. These variations are due to additions of the radiogenic isotopes Pb^{206}, Pb^{207}, and Pb^{208} produced by the decay of the uranium and thorium distributed in the sources from which the lead ores or minerals have been concentrated (Russell *et al.*, 1954). The ratios Pb^{206}/Pb^{204}, Pb^{207}/Pb^{204}, and Pb^{208}/Pb^{204} in many lead ores appear to depend largely on the time at which the minerals were concentrated and deposited, and several attempts have been made to utilize the observed isotopic ratios in lead minerals to determine the age of deposition of the minerals.

More recent lead isotope analyses have supported the conclusion that

TABLE I

RECENT AGE DETERMINATIONS ON CANADIAN ROCKS AND MINERALS

Location	Mineral	U%	Th%	Pb%	Pb^{204}	Pb^{206}	Pb^{207}	Pb^{208}	K%	A^{40}/K^{40}	Pub. Age (m.y.)	Reference
Primary Grenville Province												
Blackstone Lake Pit, Conger Twp., Ont.	U	69.3	2.99	10.72	0.007	91.96	6.66	1.38			1000[a] 993[b] 995[c] 895[d]	Wasserburg *et al.*, 1955
	FIa								11.98	0.0556	975[g]	
	FIb								11.98	0.0543	957[g]	
	FII*								1.32	0.0456	834[g]	
	FIII								10.62	0.0592	1020[g]	
One mile east of Casshabog Lake, Ont.	M								7.89	0.062	1020[g] ±70	Shill., 1955
Conc. XVI, Cardiff Twp., Ont.	U	62.29	6.61	9.92	0.0135	90.12	6.75	3.12			1026[a] 1002[b] 1020[c] 874[d]	Wasserburg *et al.*, 1955
	FI								3.02	0.0629	1070[g]	
	FII								4.79	0.0587	1020[g]	
Essonville-Tory Hill granite, Haliburton, Ont.	SpI	0.0303		0.0240	0.732	28.63	12.52	58.10			910[b]	Tilton *et al.*, 1955
	SpII	0.2205		0.0113	0.360	39.07	7.98	52.59			1090[a] 1080[a] ±25 1030[b] ±25 1060[c] ±25 390[d]	
	Zr	0.265	0.218	0.0461	<.01	85.35	6.39	8.26				
Essonville-Tory Hill granite, Haliburton, Ont. (four splits of same sample)	Zr			0.0430	Activity = 1084α/mg–hr						952[f]	Faul, 1954
				0.0415	976α/mg–hr						1020[f]	
				0.0440	1100α/mg–hr						960[f]	
				0.0428	1011α/mg–hr						1016[f]	
	I								6.15	0.0540	953[g]	Wasserburg *et al.*, 1955
	II								6.86	0.0542	955[g]	

TABLE I (*Continued*)

Location	Mineral	U%	Th%	Pb%	Pb^{204}	Pb^{206}	Pb^{207}	Pb^{208}	K%	A^{40}/K^{40}	Pub. Age (m.y.)	Reference
North of Tory Hill, Ont. (pegmatite)	F									0.054±.003	955[g]	Faul, 1954
Wilberforce, Ont.	F										1010[g]	Wetherill *et al.*, 1955
	M										1100[g]	
Churchill or Athabasca Province												
Foster Lakes, Sask.	F								9.63	0.136	1780[g] ±120	Shill., 1955
South end, lower middle Foster Lakes	F								7.55	0.148	1880[g] ±120	
Eldorado showing, Foster Lakes	F								8.93	0.103	1470[g] ±100	
	M								7.55	0.148	1880[g] ±100	
S.E. corner lower Foster Lakes	F								10.5	0.072	1150[g] ±100	
½ mile N. of Viking Lake, Sask.	U	52.9	5.24	17.14	0.005	87.37	10.09	2.53			1910[a]	Wasserburg *et al.*, 1955
											1850[b]	
											1880[c]	
											1670[d]	
	F								11.68	0.1502	1950[g]	
Keewatin-Continental Nucleus												
Huron Claim, S.E. Manitoba	F[e]								1.33	0.213	2340[g]	Shill., 1955
	M								7.60	0.235	2470[g]	
Silver Leaf Mine, Manitoba	G								3.68	0.211	2340[g]	

U, Uraninite; F, Feldspar; M, Mica; G, Greissen; F[e], albite; Sp, Sphene; Zr, Zircon.

[a]Age calculated from Pb^{207}/Pb^{206} ratio.
[b]Age calculated from Pb^{206}/U^{238} ratio.
[c]Age calculated from Pb^{207}/U^{235} ratio.
[d]Age calculated from Pb^{208}/Th^{232} ratio.
[g]Age calculated from A^{40}/K^{40} ratio.
[i]Age calculated from Pb/α ratio.

approximate ages of deposition of lead ores (and any associated minerals) can be determined in this way. By means of this method, two and perhaps three distinct periods of lead mineralization have been shown to exist in the western cordillera (Cumming *et al.*, 1955). It is apparent that the method cannot yield ages approaching in accuracy those attainable from studies of radioactive minerals. There is no doubt that the method can be useful in this restricted sense. It is important also that suites of samples from any one area be analysed in order to detect the presence of "anomalous" lead minerals which have been associated with much higher than average proportions of uranium and thorium.

The Argon-40—Potassium-40 Method

The application of this method to the determination of geological age is still in the stage of testing and development. Determination of ages from the ratio of argon-40 to potassium-40 is complicated by the dual decay of potassium-40. About 90 per cent of those potassium-40 atoms which decay, do so by emission of a beta-particle to form calcium-40. while 10 per cent transform to argon-40 by electron capture. The ratio of the decay rates of these two processes is the branching ratio, a constant which must be known in order to calculate age values. The best values of the branching ratio from counting experiments are at present 10 to 15 per cent higher than the value obtained by calculation from the A^{40}/K^{40} in potassium minerals which have been accurately dated by the uranium-lead methods. The value calculated in this way has been shown to be self-consistent for determinations on potassium feldspars ranging in age from 270 million years to 1800 million years (Shillibeer *et al.*, 1954; Wasserburg *et al.*, 1955, Shillibeer, 1955). It may therefore be useful in determining ages of potassium feldspars such as orthoclase and perthite.

In the process of checking the internal consistency of the potassium-argon method, it has been found that potassium-rich micas from the same rock as potassium-rich feldspars contain slightly higher proportions of argon-40, and would therefore give a slightly higher apparent age using the branching ratio found for feldspars (Wetherill *et al.*, 1955; Shillibeer, 1955). At present there are too few checks of this sort to establish whether some diffusion of argon from feldspars does occur, and whether any significant change in the branching value will be necessary. In addition a few results of A^{40}/K^{40} determinations on albites give slightly lower values than for associated feldspars.

Considerable losses of argon-40 have been found to occur from the very old potash-rich feldspars from Huron Claim and Silver Leaf Mine, Manitoba. The leakage from crushed samples occurring over a period of several years has been measured, but the cause of the loss has not yet been satisfactorily determined. Stevens (1955) suggests that this may be due to some metasomatic process occurring during the history of the mineral. Younger

feldspars of potash content equivalent to the Manitoba samples do not appear to lose argon on crushing (Shillibeer, 1955).

It is obvious that further work is necessary in order to clarify the status of the A^{40}/K^{40} method of dating. Trustworthy ages can apparently be determined for potassium feldspars from rocks and pegmatites ranging in age up to at least 1800 million years, and ages determined for micas appear to be valid for samples of 2500 million year age. Present indications are that rocks and minerals as young as 10 million years can be dated by this method.

In the past year, ages have been determined for samples of granitic basement rocks lying beneath the sedimentary cover to the west of the Canadian shield. These results, obtained from drill core samples, suggest that a buried orogenic belt about 1300 million years in age lies below the prairie sediments (Shillibeer, 1955).

The Rubidium-Strontium Method

Over the past few years chemical and mass spectrometric techniques have been developed which enable the small quantities of rubidium-87 and strontium-87 in muscovite and potassium feldspars to be determined with considerable accuracy. The rubidium-strontium age values determined for separated minerals from the same rocks are internally consistent, but are higher by 10 to 30 per cent than the ages obtained for the same rocks by the uranium-lead methods. There is still some uncertainty as to the accuracy of the presently accepted decay constant of Rb^{87} which may account for this difference (Wetherill *et al.*, 1955).

Conclusion

The discrepancies in age determinations introduced by such processes as loss of lead or argon leakage are a severe limitation on the type of geological problem to which age determinations may be applied The limits of reproducibility of the analytical determinations of the isotope ratios must also be considered here. The uncertainty which is attached to absolute age values may be large for geologically young samples because the percentage of original daughter product in the sample is proportionately large. For very ancient rocks and minerals, the uncertainty for ages determined by the uranium-lead methods will not be less than about $\pm$ 50 million years, even where losses of parent or daughter products are negligible. Age determinations with this large an uncertainty obviously cannot be used for close geological correlation. The most useful manner in which age determinations can be applied at present is illustrated by a paper "Dating the Precambrian of Peninsular India and Ceylon" by Holmes (1955), in which the known geological data are correlated with new and existing absolute ages to determine the relationships of Precambrian orogenic belts. Canadian age determinations have been applied in a similar manner by Cumming (1955)

in postulating a sequence of geological events in the Lake Athabasca region during the period 1850 to 1200 million years ago.

It has been mentioned that a considerable amount of work in the field of age determinations is being undertaken by research groups in Canada. A mass spectrometer has recently been set up at the Geological Survey of Canada, Ottawa, and has been used primarily for the purpose of making isotopic analyses of radiogenic leads. The facilities available at the Survey include chemical and X-ray laboratories for determining uranium, thorium, and lead, and a laboratory for making age measurements on zircons. Plans for active research on the argon-40/potassium-40 method are also underway. These facilities have been recently described by Robinson (1955).

Age studies have been undertaken at the Geophysical laboratory at the University of Toronto for the past several years. Methods being investigated at present are the A^{40}-K^{40} method, the galena method, and the lead-207 lead-206 method. A new mass spectrometer will soon be in operation and will provide greater resolution and sensitivity which it is hoped will permit ages to be determined on the trace quantities of uranium, thorium, and lead in rocks. A new line for the extraction of argon-40 from rocks is also being planned. No laboratories in Canada are at present working on the rubidium-strontium method, although some rubidium-strontium ages have been determined at McMaster University.

The new age determinations which have appeared in the literature during the past year are presented in Table I. These have been tabulated in a manner similar to the compilation of Canadian age determinations prepared by Cumming *et al.* (1955) which serves as an excellent basis for further additions. The results of the recent series of age determinations on the pitchblendes from the Lake Athabasca region have not been included in this table since the investigation is not yet complete.

In conclusion a few points regarding the present status of age determinations should be stressed. The methods of absolute age determination do not appear to be fundamentally faulty. It should be possible to clear up the existing discrepancies by analysing suites of samples rather than single specimens, or by redetermining decay constants with increased accuracy. The existence of these discrepancies may slow up progress in applying age determinations to specific geological problems, but at the same time they may give further information about geological processes which have occurred during the history of the samples.

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SECTION FOUR

Archaeocyatha from the McDame Area of Northern British Columbia

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ABSTRACT

Archaeocyatha from the Lower Cambrian Atan group from the McDame area of northern British Columbia are described. The fossils occur in a limestone band at approximately 129° 00′ longitude and 59° 15′ north latitude. Three orders, the Ajacicyathida, the Metacyathida, and the Syringocnemida of the phylum Archaeocyatha are represented. Six new species are described; these are: *Archaeocyathus loculiformis, Archaeocyathus borealis, Archaeofungia obliqua, Metacoscinus gabrielsensis, Metacoscinus deasensis* and *Syringocyathus canadensis*. The fauna has several species in common with that of the Donald formation of the Purcell Mountains, and indicates that, in part at least, the Atan group is Lower Cambrian in age.

DURING the summers of 1950 to 1953 Dr. H. Gabrielse of the Geological Survey of Canada mapped the McDame area of northern British Columbia. In the course of his field work, Dr. Gabrielse discovered and collected a large number of Archaeocyatha of Lower Cambrian age. Through the courtesy of Dr. Gabrielse and Dr. Hans Frebold, Chief, Division of Stratigraphic Palaeontology, the writer was given the opportunity to examine and to describe the collection.

The fossils occur in the grey, tan, and black limestone assigned to the Atan Group. The preservation of the specimens is unusually good. With the possible exception of the ones from Silver Peak, Nevada, and Waucoba Springs, California, they are the best so far collected from the Cordilleran region. The fossil localities are marked on Preliminary Map no. 54-10, sheet 104 p, published by the Geological Survey, Canada, in 1954. The locality is approximately at 129° 00′ long. and 59° 15′ lat. The general area can be reached by automobile from Watson Lake on the Alaska Highway, but travel within the area is practicable only on foot or by horse.

The Atan Group is described by Dr. Gabrielse in the following terms: "Fossiliferous rocks of the Atan Group, comprising over 14,000 feet of sedimentary rocks, occupy a northwesterly trending complex anticlinorium, and the southwest limb of a large syncline. . . . The base of the Cambrian strata has not been recognized. Highly contorted rocks of the Walker Group overlie the Atan Group with little, if any, structural discordance." The Atan Group is considered to be of Lower and Middle Cambrian Age The Walker Group is assigned Ordovician Age.

The presence of Olenellid trilobites in the rocks of Atan Group, within the same area, confirms the age determination based on the Archaeocyatha.

The McDame fauna has a strong resemblance to the Donald fauna of the Purcell Mountains farther south. The very common species *Coscinocyathus dentocanis* and *Pycnoidocyathus columbianus* are present in both. However, *Metacoscinus gabrielsensis* n.sp. and *M. deasensis* n.sp. apparently do not occur farther south. *Ethmophyllum ratum* and *Archaeocyathus latus* are suggestive of affinities with the Cambrian of Siberia. The very common *Ajacicyathus nevadensis* and *Ethmophyllum whitneyi* of California and Nevada are either absent or very rare. On the whole the fauna is dominated by the Coscinocyathidae and Metacoscinidae, which is also true of other British Columbia localities. This is in contrast with the dominant Ethmophyllidae of the southern Cordilleran region and the Archaeocyathidae of Labrador.

List of Archaeocyatha Present in the McDame Area

Phylum Archaeocyatha
Class Archaeocyathea
Order Ajacicyathida

Family Ajacicyathidae
Ajacicyathus nevadensis (Okulitch)
A. undulatus Okulitch

Family Ethmophyllidae
Ethmophyllum sp.
Ethmophyllum cf. *ratum* Vologdin
Thalamocyathus sp.

Family Coscinocyathidae
Coscinocyathus dentocanis Okulitch
Coscinocyathus sp.

Order METACYATHIDA

Family Archaeocyathidae
Archaeocyathus atlanticus Billings
A. cf. *latus* (Vologdin)
A. loculiformis n.sp.
A. borealis n.sp.
Archaeopharetra sp.

Family Pycnoidocyathidae
Pycnoidocyathus amourensis (Okulitch)
P. columbianus (Okulitch)
Archaeofungia obliqua n.sp.
Archaeofungia sp.

Family METACOSCINIDAE

Metacoscinus gabrielsensis n.sp.
M. deasensis n.sp.
Archaeosycon sp.

Order SYRINGOCNEMIDA

Family SYRINGOCNEMATIDAE

Syringocyathus canadensis n.sp.

*

DESCRIPTION OF SPECIES

Family AJACICYATHIDAE Bedford and Bedford, 1939

Ajacicyathus nevadensis (Okulitch)
Archaeocyathus nevadensis Okulitch, 1935
Ajacicyathus nevadensis (Okulitch), 1943

Plate II; Fig. 2

The specimen is marked V 27 A, 17541; it is exposed by a single transverse section. The diameter is 8.5 mm., width of intervallum is 2.5 to 3.0 mm., diameter of central cavity is nearly 3 mm., giving an intervallum coefficient of 0.8.

The parieties are thin, straight, 24 in number, giving a parietal coefficient of 3. Details of outer and inner walls are lacking, but apparently both walls were thin and simple. The specimen, therefore, agrees very closely to the type specimen from Nevada, whose intervallum coefficient is 0.7, and the parietal coefficient is 4. The slight difference in the coefficients is not sufficient to remove the specimen to another species.

Geological Survey of Canada, collection no. 12360

Ajacicyathus undulatus Okulitch, 1948

Plate II; Fig. 9

The specimen is marked V-9A, 17541. It is a fragment of a very large ajacicyathid with narrow intervallum and probably somewhat flexible walls. Vologdin (1931) described similar forms under the names *Archaeocyathus clarus* and *A. arteintervallum* from the Lower Cambrian of Siberia. A similar form was described by Okulitch, 1948, from the Purcell Mountains near Golden, B.C.

The diameter of the cup can not be obtained, since only a small fragment of it is available. The width of the intervallum is 1.5 mm. The parieties are spaced from 0.3 mm. to 0.7 mm. apart, with 0.5 mm. being close to the average. The outer wall is thin and has numerous small pores. Three to nine pores occur within the intersept. The inner wall is three to four times as thick as the outer wall and is perforated by fairly large pore-canals.

Some of the pore-canals are slightly oblique to the inner surface of the wall. The parieties are simple, thin, and radial. They are perforated by a small number of large pores.

Geological Survey Canada, Collection no. 12361

Family ETHMOPHYLLIDAE Okulitch, 1943

Ethmophyllum cf. *ratum* Vologdin

Ethmophyllum ratum Vologdin, 1940

Plate III; Figs. 8, 9

The species is represented by two specimens marked V-22, 17541 and V-23, 17541. The V-22 is a cross-section; the V-23 is an oblique section.

The description is based on both specimens. The diameter is 10 mm., the width of the intervallum is 1.5 mm., and the diameter of the central cavity is 7 mm. The number of parieties is 64. The parietal coefficient is, therefore, about 6.4. The intervallum coefficient is about 4.0.

The cup is acutely conical to cylindrical in shape. The outer wall is thin appearing as a dotted line, because of numerous small pores. Nine to twelve pores appear per intercept. The parieties are thin, irregular, radial, with few or no pores. The inner wall is thick, appearing as a net of rounded pores arranged in compact quincunx. The pores are actually canals arranged obliquely to the wall, and, therefore, appear as sub-circular vesicles on random cross-sections.

Affinities: The species is nearest to *E. ratum* Vologdin, from which it differs in a lower parietal coefficient (6.4 as against 7.5 of the holotype) and the details of the inner wall. The differences do not appear to be important enough to warrant a description of the specimens as new species.

Geological Survey Canada, Collection nos. 12370, 12371

Thalamocyathus ? sp.

Thalamocyathus Gordon, 1921

Archaeocyathus trachealis Taylor, 1910

Cyclocyathus Vologdin, 1931

Bronchocyathus Bedford, 1936

Plate III; Fig. 2

The genus belongs to the Family Ethmophyllidae, possesses a finely porous outer wall, numerous thin parieties, and an inner wall characterized by horizontal, annular shelves or rings, and minor structures projecting into central cavity. The genus is represented in the collection by a single specimen exposed by a longitudinal section. The specimen is 33 mm. long and about 7 mm. wide at the upper end. The lower end (Spitz) is broken off or dissolved away. The intervallum is 2 mm. wide, and the central cavity 3 mm. wide at the upper end, giving an intervallum coefficient of 2:3 or 0.66.

The outer wall is very thin, perforated by numerous closely-packed pores, resulting in exceedingly delicate mesh. The inner wall is perforated by relatively coarse V-shaped canals. The inner edges of the canals result in the annular rings, visible in cross-sections, characteristic of the genus. Since neither a transverse section nor a vertical tangential section grazing the inner wall is available, it is impossible to identify the specimen specifically. Even the generic identification is open to some doubt and the specimen may possibly be an *Ethmophyllum* with a modified canal structure of the inner wall.

Geological Survey Canada, Collection no. 12365

Family COSCINOCYATHIDAE Taylor, 1910

Coscinocyathus dentocanis Okulitch

Okulitch, 1943, pl. 4

Okulitch, 1948, p. 342

Plate III; Figs. 5, 6, and 7

The species was originally described from the Dogtooth Range of Purcell Mountains. The present collections contain much better specimens than the holotype, permitting additional observations. The original description based on specimen no. 9516, Geological Survey of Canada, reads as follows:

"The specimen is a weathered-out, longitudinal section in light-gray limestone.

General shape: Tubular, with very slight taper. Reconstructed diameter must have been about 22 mm., and height about 60 or 70 mm., of which 50 mm. is visible. Width of intervallum is 5 mm., where diameter of central cavity is 12 mm., giving an intervallum coefficient of 5:12 or 0.4. Outer wall probably thin and simple. Intervallum is crossed by radial vertical parieties and tabulae slightly convex upward. Resultant rectangular cells or loculi are about twice as high as wide; 14 parieties occur in space of 1 cm., giving a parietal coefficient of about 4.5; tabulae are about 1.5 mm. apart. Inner wall is apparently smooth and single, without any structure projecting into central cavity." Three best specimens of this species in the present collection afford the following information:

	G.S.C.12368	G.S.C. 12359	G.S.C.12367
Average diameter	25 mm.	22 mm.	25 mm.
Height	70 mm.	38 mm. (fragment)	
Av. central cavity	11 mm.	12 mm.	15 mm.
Width of intervallum	5 mm.	5 mm.	5 mm.
No. of parieties	100 ±	92	110
Parietal coefficient	4.0	4.2	4.14
Interval. coefficient	5:11=0.45	0.41	3.3
Dist. between parieties	0.4 mm.	0.5 mm.	0.5 mm.
Dist. between tabulae	1.5 mm.	1.5 mm.	1.5 mm.

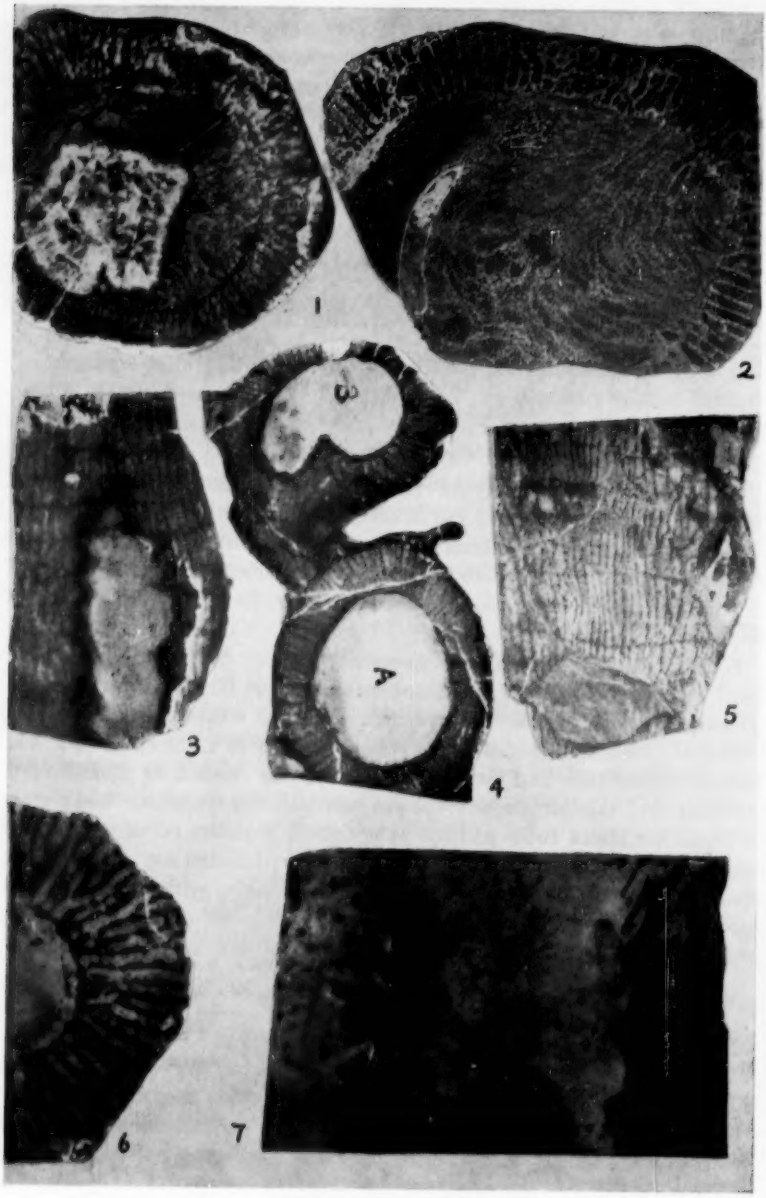

PLATE I

Thus, all the major numerical relationships are very close to the holotype. The inner wall of specimen no. 12359 is exposed. It is a coarse net consisting of elongated, rectangular openings about 0.7 mm. long and 0.1 mm. high. This species of *Coscinocyathus* appears to be one of the most common in the Cordilleran Region of Canada.

Geological Survey Canada,
Collection nos. 12368, 12359, 12367

Coscinocyathus sp.

Several fragments of poorly preserved *Coscinocyathus* are present. Most of them are possibly *C. dentocanis* but their preservation or fragmentary nature prevents closer identification.

Family ARCHAEOCYATHIDAE

Genus *Archaeocyathus*

Archaeocyathus atlanticus Billings

Archaeocyathus atlanticus Billings, 1861

Plate III; Fig. 1

The species is represented in the collection by several, poorly preserved specimens and one exceptionally good one. This specimen, numbered V-11, is described. The specimen is exposed by a transverse section.

Diameter	9 mm.
Diam. of c.c.	5 mm.
Width of intervallum	2 mm.
Intervallum coef.	2:5 = 0.4

The intervallum is, therefore, much narrower than in the holotype (no. 369, Geological Survey Canada). However, the general variability of this species makes me include the specimen in *A. atlanticus*. It seems that it is closer to *A. atlanticus* described by Okulitch (1948) from the Purcell Mountains than the Labrador species. The intervallum is filled with num-

PLATE I

1. *Metacoscinus gabrielsensis* n.sp. X 1.7. Holotype, G.S.C. no. 12357.
2. *Metacoscinus gabrielsensis* n.sp. X 2.5. Thin section of holotype G.S.C. no. 12357. Shows intervallum structure and fine skeletal tissue in the central cavity.
3. *Metacoscinus deasensis* n.sp. X 2.7. Holotype, G.S.C. no. 12358 B. Longitudinal section showing part of the intervallum, central cavity, and the spacing of tabulae.
4. *Metacoscinus deasensis* n.sp. X 1.5. Holotype, G.S.C. no. 12358 A. Cross section of two specimens; holotype is marked "A."
5. *Metacoscinus gabrielsensis* n.sp. X 1.7. Holotype, G.S.C. no. 12357. Longitudinal section, grazing inner wall, showing parieties and tabulae.
6. *Archaeofungia obliqua*, n.sp. X 2.5. Holotype, G.S.C. no. 12353. Cross section showing inner wall and intervallum structures.
7. *Archaeofungia obliqua* n.sp. X 3. Holotype, G.S.C. no. 12353. Longitudinal section showing central cavity, and inner walls with oblique canals.

erous, curved taeniae, leaving tortuous passages in between. The outer wall is thin, smooth, and perforated by numerous, small pores. The inner wall is made largely by coalescence of inner edges of the taeniae, producing a coarse and probably irregular net.

The species is world wide in its distribution.

Geological Survey Canada, Collection no. 12363

Archaeocyathus cf. *latus* (Vologdin)
Spirocyathus latus Vologdin, 1940

Plate III; Fig. 3

The specimen is exposed by a polished and natural cross-section. The dimensions are:

Diameter	26 mm.
Dia. of c.c.	15 mm.
Width of int.	5 to 6 mm.
Int. coeff.	$5:15 = 0.33$

The intervallum is filled by slender and not-too-crowded taeniae and some vertical pillars. The walls are fairly thick (about 0.25 mm.) and perforated by widely spread pores 0.25–0.30 mm. in diameter. The species differs from *A. atlanticus* in having a narrower intervallum (int. coeff. = 0.33 instead of 0.9) and fewer taeniae. It seems to be nearest to *A. latus* (Vologdin) from which it differs in having a slightly wider intervallum, and heavier construction of the taeniae. The specimen may, therefore, represent a new species. However, since only one specimen is available at present, it seems best to refer it to the nearest similar species, until more material becomes available.

Geological Survey Canada, Collection no. 12364

Archaeocyathus loculiformis n. sp.

Plate II; Fig. 3

The description of the species is based on a single specimen exposed in a transverse and longitudinal section. The characteristics so exposed are so different from all other species of *Archaeocyathus* that, at first glance, it may be difficult to decide whether or not the species belongs to a new genus. The specimen has the following measurements:

Diameter	14 mm.
Length	30 mm. (end broken off)
Width of intervallum	3.5 mm.
Dia. of c.c.	7 mm.
Int. coeff.	$\frac{3.5}{7} = 0.5$
Parietal coeff.	indeterminable

General shape is gently tapering, sub-cylindrical. The outer wall is thin, dense with no clearly marked pores—the pores are presumably small and spaced irregularly. The intervallum, the most distinctive part of the specimen, is filled with curving taeniae, so arranged that in cross-section the intervallum appears to be filled by irregular sub-circular loculi or vesicles. The loculi are in communication with each other by large pores or passages. In vertical section the loculi are greatly elongated in a direction nearly paralleling the axis of the specimen; thus assuming the appearance of large, longitudinal canals. Some of the loculi are inclined to the axis and emerge as large pores of the inner wall. Some appear to be inclined towards the outer wall. The taeniae, particularly those close to the outer wall, in places assume the position of incomplete tabulae.

The *inner wall* is very thin, somewhat irregular, and is perforated by the lower ends of loculi and the smaller pores.

The *central cavity* is filled at its lower end by irregular vesicles and trabecular tissue. The upper portion is empty except for occasional "plumes" of vesicular tissue issuing from the inner wall and resembling the more common extensions and laminae of exothecal tissue.

The species has no close similarities to any other species of *Archaeocyathus*, the nearest possibility being *A.* (*Retecyathus*) *laqueus* Vologdin. A somewhat greater development of near-horizontal taeniae would place it close to genus *Claruscyathus* Vologdin, of the Metacoscinidae. A greater regularity of the loculi, to make them more tube-like, would produce a form not unlike *Syringocyathus* Vologdin, of the *Syringocnematidae*. This remote similarity to genera of widely different families suggests the *A. loculiformis* n.sp. is a rather generalized primitive form from which, with only minor structural changes, a widely different Archaeocyatha could be derived.

Geological Survey Canada, Holotype, no. 12354

Archaeocyathus borealis n.sp.

Plate II; Fig. 1

The new species is a small *Archaeocyathus* which differs from all previously described species of the genus in having extremely numerous and fine pores in the outer wall and a relatively delicate network of taeniae in the intervallum. The specimen has a sub-cylindrical general shape, a narrow central cavity and an intricate network of taeniae in the intervallum.

Diameter	13 mm.
Dia. of c.c.	3 mm.
Width of intervallum	5 mm.
Int. coeff.	5:3 = 1.66

The *outer wall* is a thin continuous sheet and is perforated by numerous, very fine, pore-canals. In this respect, the species differs considerably from

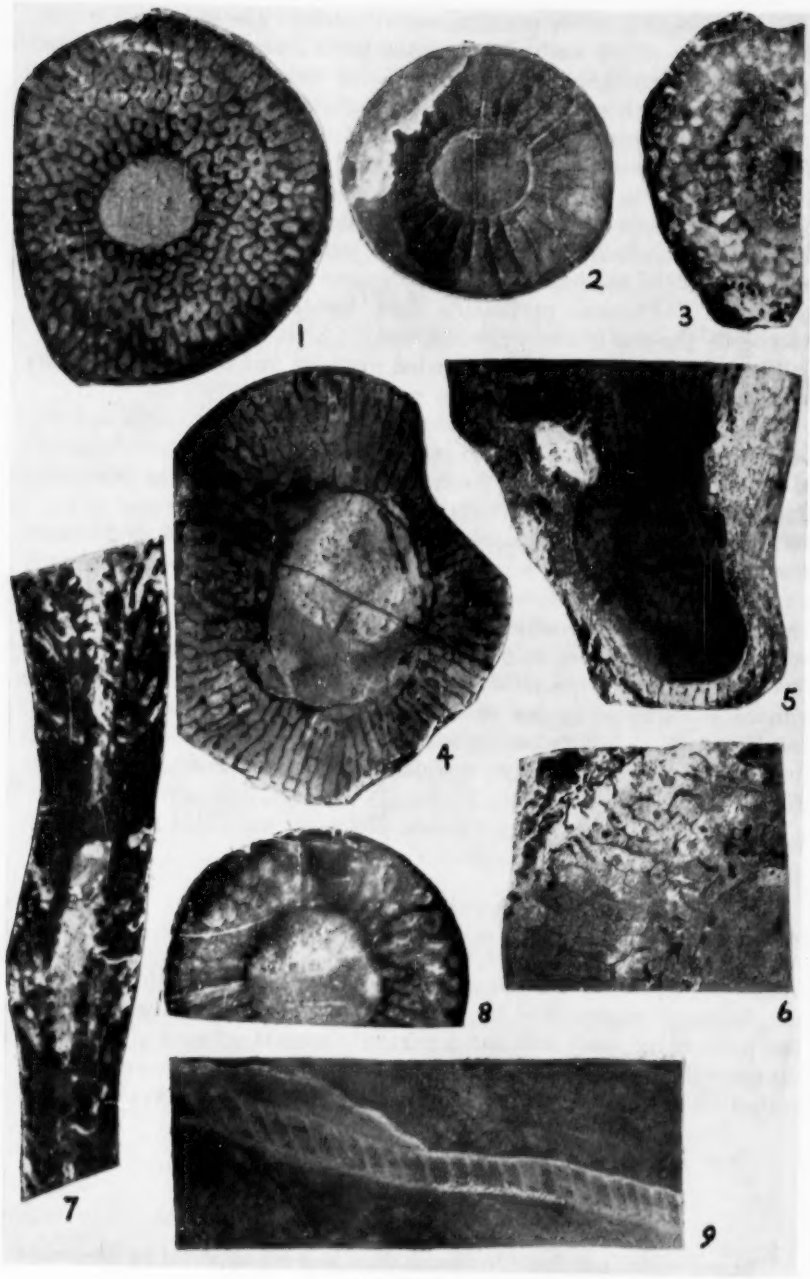

PLATE II

either *A. densus* (Vologdin) or *A. yavorskii* (Vologdin) which have the outer wall made up of anastomising ends of taeniae.

The *intervallum* is relatively wide and is filled by a light network of taeniae. Large openings and passageways permitted flow of water from vesicle to vesicle. The taeniae are more regular near the outer wall with a noticeable tendency towards radial arrangement. This feature is noteworthy as it is more common for taeniae to be radial near the inner than the outer wall.

The *inner wall* is made up of the ends and edges of taeniae. The openings of the intervallum passages are commonly covered by thin, inwardly bulging vesicles or pellis.

The *central cavity* is narrow and tubular, clear of all skeletal tissue in the upper part of the cup. Lower portion and spitz are unknown.

The new species resembles *A. atlanticus* in the nature of its outer wall and cylindrical shape, but differs from it in having more slender and intricate taeniae in the intervallum and in intervallum coefficient of 1.66 instead of 0.9. The species also resembles *A. densus* and *A. yavorskii* in the nature of the taeniae but differs from both in having a minutely perforate and sheath-like outer wall and a different intervallum coefficient.

Geological Survey Canada, Holotype, no. 12355

Archaeopharetra sp.

Small, globular-to-rounded, conical Archaeocyathids, lacking a distinct inner cavity. The outer wall is perforated by small pores and the interior is filled by a variety of taeniae, rods and dissepiments. The specimens may not be distinct genera and species but very young Metacyathidae.

Geological Survey Canada, Collection no. 12372

PLATE II

1. *Archaeocyathus borealis* n.sp. X 4.6. Holotype, G.S.C. no. 12355. Cross section showing outer and inner walls, narrow central cavity, and structure of intervallum.
2. *Ajacicyathus nevadensis* (Okulitch) X 5. G.S.C. no. 12360. Cross section, showing simple radial parieties.
3. *Archaeocyathus loculiformis* n.sp. X 4. Holotype, G.S.C. no. 12354. Cross section showing loculi-forming taeniae and some vesicular tissue in the central cavity.
4. *Pycnoidocyathus columbianus* (Okulitch) X 1.5. G.S.C. no. 12362. Cross section.
5. *Pycnoidocyathus columbianus* (Okulitch) X 1.33. G.S.C. no. 12362. Longitudinal section cutting intervallum.
6. *Pycnoidocyathus columbianus* (Okulitch) X 3. G.S.C. no. 12363. Cross section showing details of intervallum structures and inner and outer walls.
7. *Syringocyathus canadensis* n.sp. X 4. Holotype, G.S.C. no. 12356. Longitudinal section, showing obliquely directed loculi or canals of the intervallum and large pores of inner wall.
8. *Pycnoidocyathus amourensis* (Okulitch) X 3.5. G.S.C. no. 12366. Cross section, showing central cavity, and intervallum with parieties and dissepiments.
9. *Ajacicyathus undulatus* Okulitch, X 3.66. G.S.C. no. 12361. A portion of a large specimen showing walls and intervallum.

Family PYCNOIDOCYATHIDAE Okulitch, 1950

Pycnoidocyathus amourensis (Okulitch)
Cambrocyathus amourensis Okulitch, 1943
Pycnoidocyathus amourensis (Okulitch), 1950

Plate II; Fig. 8

This common, eastern species is very rare in the Cordilleran Region. None have previously been reported from other Lower Cambrian localities in British Columbia. It is represented by two specimens marked V-10, and V-12-17541 in the collection. The better specimen, V-12, agrees in almost all particulars with the holotype from Labrador. The specimen is tubular or cylindrical in general shape. The lower portion is missing. Its other characteristics are as follows:

Diameter	14 mm.
Dia. of c.c.	6 mm.
Width of intervallum	4 mm.
Number of parieties is 26 per over all dia. of 14 mm.	
Parietal coefficient	2.6
Intervallum coefficient	4:6 or 0.66 exactly like the holotype
Length of fragment	26 mm.

Outer wall—thin, apparently perforated by numerous pores.

Intervallum—parieties irregular to regular, occasionally branching, synapticulae and dissepiments are present.

Inner wall—perforated by large pores, one pore per intercept.

Annulations—less pronounced than in the eastern species, spread about 10 mm. apart.

Remarks: Very similar to the holotype, from which it differs in having larger and fewer pores in the inner wall.

Geological Survey Canada, Collection no. 12366

Pycnoidocyathus columbianus (Okulitch)
Cambrocyathus columbianus Okulitch, 1943
Cambrocyathus columbianus Okulitch, 1948

Plate II; Figs. 4, 5, and 6

This is one of the most common species in the collection. The species was first described from the Lower Cambrian in the Purcell Mountains and is apparently a common member of the Archaeocyathid faunas in the northern portion of the Cordilleran geosyncline. A closely related species is *P. ceratodictyoides* (Raymond) which occurs in California and Nevada. The difference between these species is largely that the southern species has prominent transverse annulations, which are absent, or weakly developed in the northern. The intervallum and parietal coefficients are also different.

The *general characteristics* of the McDame species are very close to those of the holotype from the Purcell Mountains.

The *general shape* is a gently tapering cone, showing some gentle transverse annulations.

The *diameter* varies between 16 mm. and 42 mm. in different specimens.

The *central cavity diameter* correspondingly varies between 9 mm. and 22 mm., giving a very constant intervallum coefficient of between 0.41–0.45.

The *intervallum* is crossed by fairly numerous parieties carrying synapticulae and dissepiments. The number of parieties, depending on the size of the specimen, varies between 42 and 100, resulting in a parietal coefficient of between 2 to 3.5. The variability of this coefficient is greater than usual and may throw some doubt on its usefulness. However, in most specimens the parietal coefficient is close to 3.0.

The *walls* are perforated by small pores.

The *inner wall* in one specimen seems to have ring-like structures similar to those of *Annulocyathus* Vologdin. This structure is not clear, however, and may be accidental.

Geological Survey Canada, Collection no. 12369

Archaeofungia obliqua n.sp.

Plate I; Figs. 6, 7

The genus *Archaeofungia* and its invalid synonyms *Metafungia* Bedford, and *Sibirecyathus* Vologdin, is regarded as a subgenus of *Pycnoidocyathus*. It differs from *Pycnoidocyathus* in the absence of transverse annulations of its outer wall.

The holotype of the new species is about 60 mm. long, the *diameter* of the upper end is over 30 mm., and the diameter of the lower end is about 25 mm. The specimen is, therefore, subcylindrical, with a very slight taper. The intervallum is 7–8 mm. wide, and the central cavity varies between 12 mm. and 17 mm. in width.

The *intervallum coefficient* is about 0.5; 64 parieties cross it where the diameter is 25 mm., giving a parietal coefficient of $\frac{64}{25} = 2.6$.

The *outer wall* is worn off, so it is impossible to get any information on its characteristics.

The *inner wall* consists of edges of canals directed obliquely upwards into the central cavity. The size of pores or canal openings varies between 0.5 mm. to slightly over 1 mm. in diameter.

The *intervallum* is filled by relatively thick perforated parieties. The parieties tend to weave, and occasionally branch. They carry numerous synapticulae and possibly some dissepiments. All skeletal elements are perforate. The new species differs from all other species of Archaeofungia in having the oblique canals which open into the central cavity.

Geological Survey Canada, Holotype, no. 12353

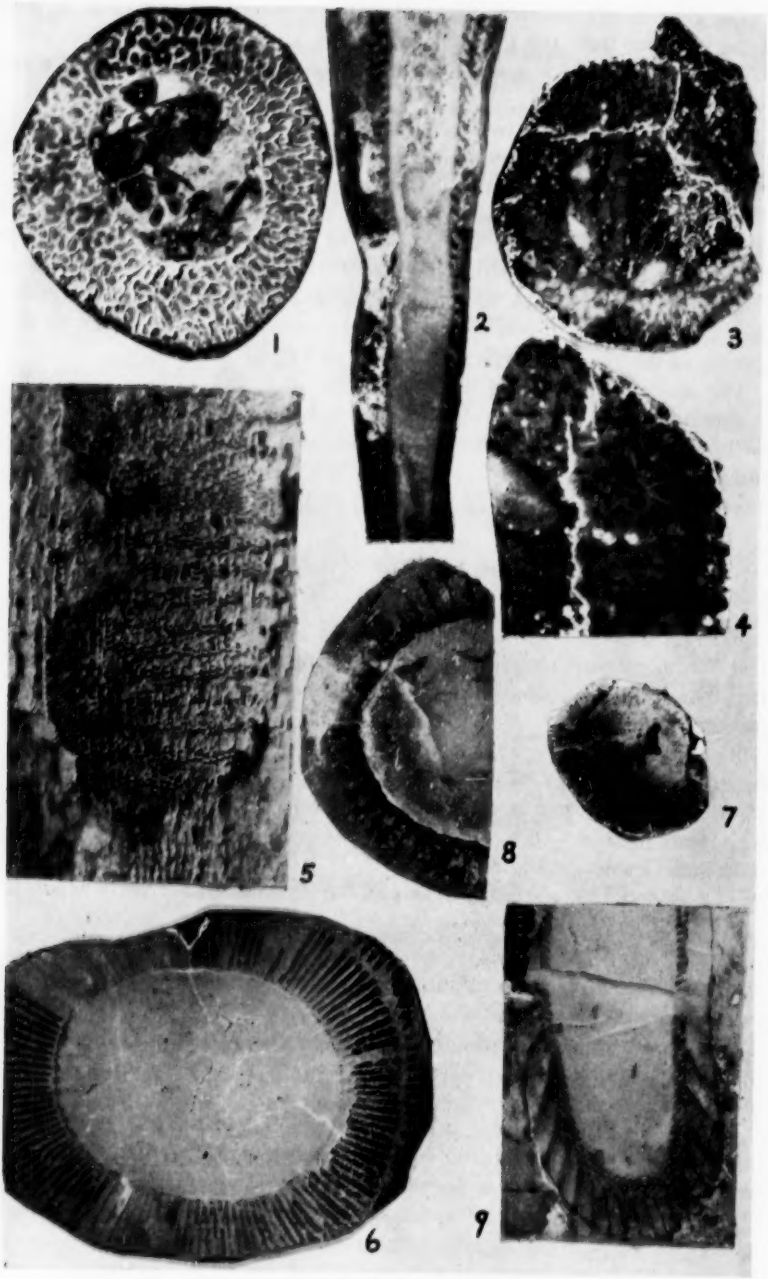

PLATE III

Family METACOSCINIDAE Bedford and Bedford, 1932

Metacoscinus Bedford, 1934

The genus was first described from the Lower Cambrian of Australia by Bedford. Its characteristics are: conical cups, with regular parieties in the upper part of the cup. The lower portion lacks the central cavity, the entire cup being filled with vesicular tissue. Porous tabulae are present at irregular intervals.

Metacoscinus gabrielsensis n.sp.

Plate I; Figs. 1, 2, and 5

The species is represented by one, well-preserved specimen. The original specimen has been reduced in size for the preparation of polished and thin sections.

The *larger diameter* is 30–35 mm.

The *smaller diameter* (about one inch below) is 25–30 mm.

The *width of the intervallum* is 5 mm., resulting in an intervallum coefficient of about 5:20 or ¼.

The *number of parieties* is approximately 110, giving a parietal coefficient of about 3.4. The number of parieties can not be counted accurately because of branching or disintegration into dissepimental tissue. The specimen is, in part, enveloped by exothecal tissue.

The *outer wall* is thin, perforated by numerous, closely spaced, simple, rounded pores, arranged without any special order. One to six pores occur per intersept.

The *intervallum* is crossed by fairly regular parieties of *Pycnoidocyathus* type. The parieties are perforated by fairly large numerous pores, and are interconnected by very delicate vesicular dissepimental tissue. Some parieties branch and curve, others are straight and simple. The intervallum is also

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PLATE III

1. *Archaeocyathus atlanticus* Billings X 6. G.S.C. no. 12363. Cross section, showing the relatively narrow central cavity and complicated taeniae in the intervallum.
2. *Thalamocyathus* sp. X 4. G.S.C. no. 12365. Longitudinal section, showing the "V" shaped canals of inner wall.
3. *Archaeocyathus* cf. *latus* (Vologdin) X 1.6. G.S.C. no. 12364. Cross section of a portion of intervallum, showing outer and inner walls and spicule-like taeniae in the intervallum.
5. *Coscinocyathus dentocanis* Okulitch X 3.5. G.S.C. no. 12359. Naturally weathered out inner wall, showing its lattice-like structure.
6. *Coscinocyathus dentocanis* Okulitch X 2.5. G.S.C. no. 12367. Cross section, showing central cavity, inner wall, and regular radial parieties in the intervallum.
7. *Coscinocyathus dentocanis* Okulitch X 1. G.S.C. no. 12359. Cross section, showing very clearly the pores of the inner wall.
8. *Ethmophyllum* cf. *ratum* Vologdin X 5. G.S.C. no. 12370. Cross section, showing details of inner wall.
9. *Ethmophyllum* cf. *ratum* Vologdin X 4. G.S.C. no. 12371. Slightly oblique longitudinal section, showing parieties and mesh-like inner wall.

crossed by flat irregularly spaced tabulae. The spacing differs from 3 mm.–11 mm., with 6 mm. being apparently average. The tabulae are perforated by numerous closely-set pores.

The *inner wall* is single, smooth, thin, perforated by numerous pores, only slightly larger than the pores of outer wall.

The *central cavity* is the most characteristic feature of the specimen. Its lower portion is completely filled with fine, labyrinthine mass of laminar, and almost spicular, skeletal elements. This skeletal framework resembles the intervallum structures of Archaeocyathidae; in particular that of *Protopharetra*, or the finer varieties of exothecal tissue. Upwards from the base, the central cavity appears, and the vesicular tissue tapers out, becoming a lining on the inner wall. Intermediate sections show, therefore, a second intervallum made of this tissue lining the central cavity side of the inner wall. This resembles the structure of *Tercyathus*, and if it was not for the tabulae, the specimen could be mistaken for this genus. The lining is irregular in thickness and has a distinct inner wall of its own. The possibility exists that the vesicular tissue of the central cavity is a symbiont or a parasite.

Specimen no. 17542, V-18 is described as the holotype, G.S.C. collection no. 12357. The specific name is proposed in honour of Mr. Gabrielse of the Geological Survey of Canada.

Metacoscinus deasensis n.sp.

Plate I; Figs. 3 and 4

This species is represented by three, very good specimens. Specimen V-1 A (12358) is designated as the holotype.

Diameter is 23–27 mm. The length of the fragment is 45 mm. The original length could easily have been 80–100 mm. Taking average measurements, the dimensions are as follows:

Intervallum	5 mm. wide
Central cavity	16 mm. in diameter
Number of parieties	about 94
Intervallum coefficient	approx. 5:16 or 0.33
Parietal coefficient	approx. 94 ÷ 25 or about 3.76

The *outer wall* is thin, perforated by numerous pores, 2–3 pores occurring per intersept.

The *intervallum* is crossed by numerous, regular, radial and porous parieties; porous, net-like, tabulae; and considerable amounts of dissepimental and vesicular tissue. The tabulae are spaced 2 to 3 mm. apart.

The *inner wall* is a thin, irregularly porous mesh.

The *central cavity* is empty and shows no skeletal tissue of any kind.

The species is undoubtedly closely related to *M. gabrielsensis* n.sp., from which it differs mainly in the absence of vesicular tissues in the central

cavity. Should it be shown that the central cavity tissue of *M. gabrielsensis* is extraneous, I would favour including *M. deasensis* in *M. gabrielsensis.*

Geological Survey Canada, Holotype, no. 12358

Family SYRINGOCNEMATIDE Taylor, 1910

Syringocyathus canadensis n.sp.

Plate II; Fig. 7

The Holotype no. 12356 (marked V-13, 17541) is a narrow, elongated, acutely conical cup, 50 mm. long before cutting, and having a maximum diameter of 5 to 6 mm.

The *diameter of the central cavity* is 1.5 mm. and the average *width of the intervallum* about 2 mm. Intervallum coefficient is, therefore, 2: 1.5 = 1.3.

The *outer wall* is perforated by coarse pores. The intervallum is filled by elongated, subprismatic, and rounded loculi or tubes oriented obliquely to the axis of the specimen. The loculi proceed upward and outward from the inner to outer wall, making an angle of 30° with the axis.

The *inner wall* is made up of large pores, of 0.3 mm. in diameter. These openings connect the inner cavity with the loculi of the intervallum. The walls of the loculi are perforated all along their length.

The species is fairly close to the Siberian species *Syringocyathus aspectabilis* Vologdin. It differs from it in having fewer and coarser elements in the intervallum and a different intervallum coefficient (1.3 against 0.75). The pores of the inner wall are also much coarser. The new species is also similar to the Mexican *S. inyoensis* Okulitch, but differs from it in the greater regularity and small number of its loculi.

Geological Survey Canada, Holotype, no. 12356

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SECTION FOUR

The Physics of Orogenesis in the Light of New Seismological Evidence*

A. E. SCHEIDEGGER

Presented by J. T. WILSON, F.R.S.C.

ABSTRACT

During the past twenty years, many studies of the displacements which are taking place during the occurrence of an earthquake in its focus, have been published by various authors. In the present paper, the results of these studies have been collected and their bearing upon the physics of orogenesis has been analysed. It will be seen that the main features of the displacements within the Earth's mantle and crust are, first, that they are localized in almost planar zones dipping at some intermediate angle beneath recent mountain and island belts; second, that the material of which the Earth's mantle is composed exhibits the characteristics of an elastic after-effect; and third, that the differential displacements are to a large extent horizontal (transcurrent), i.e. *not* parallel to the dip of the planar zones.

A renewed discussion of the possible mechanics in the Earth's mantle and crust shows that there is seemingly no known mechanical model-material which would entertain the displacements as they are found in the Earth. It might therefore be necessary to postulate a new type of model-material with a mechanical behaviour not heretofore encountered in the laboratory. What is required is a mechanical material in which, during failure, the direction of the differential displacements would not coincide with the surface of rupture.

The ultimate elucidation of the process of orogenesis depends on the theoretical understanding of the mechanical behaviour of the material in the Earth's mantle under the there prevailing conditions; this has not yet been achieved.

I. Introduction

IN investigating the physics of the forces in the Earth's crust one is faced with the condition that no coherent theory is known from which all the details would follow. In contrast to most physical theories, where a fundamental equation is postulated whose consequences (more or less) agree and thereby "explain" the facts of nature which they concern, the cause of orogenesis (i.e., mountain-building) is still much in the dark. The only attack on the problem is therefore by the inductive method.

The inductive method consists first, in accumulating as many pertinent facts about the physiography of the Earth as possible, and secondly, in testing a multitude of conceivable hypotheses of orogenesis in the face of these facts. It is hoped that then one of the hypotheses devised will more or less agree with the physiographic facts.

The task of uncovering the cause of orogenesis is hampered by two obstacles. First, not much is known of the conditions at those depths in the

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Earth at which orogenesis presumably originates. Secondly, even if these conditions were known, one would have to face the difficulty that they would certainly involve temperatures and pressures which cannot be duplicated in the laboratory and thus the behaviour of matter under these conditions would remain practically unknown. All that can be hoped for, therefore, is that intelligent guesses can be made as to the cause of orogenesis which will be consistent with known physical theories.

In the face of our ignorance about many of the pertinent conditions in the Earth and the behaviour of matter under conceivable conditions, it is not surprising that not one but many theories of orogenesis are in existence. Some years ago, the present writer gave an examination of the physics of such theories of orogenesis in the light of the then known physiographic facts (Scheidegger, 1953). In brief, it was shown there that geologists and geophysicists are generally agreed that orogenesis must take place either in the crust or in the upper part of the mantle of the Earth with the core playing only an indirect part as heat supplier or the like. Thus, it is natural to assume that orogenesis takes place in a rather thin layer which may be termed the orogenetic shell of the Earth. Since the mechanical behaviour of matter at the depth of the orogenetic shell is not known, it is conceivable that the latter might have any mechanical properties ranging from those of a brittle shell to those of a layer of a liquid below the crust. It was furthermore shown that only two physical mechanisms gave a reasonable agreement with what were then considered physiographic facts: the convection current hypothesis and the contraction hypothesis of a cooling Earth. In both cases, crustal shortening is obtained which seems to be basic to the process of mountain-building. In either case, the motion is one of thrust-faulting at the surface of the Earth. The convection hypothesis assumes a process of slowly rotating currents in the mantle which produce the crustal shortening, whereas the contraction hypothesis assumes a process of cooling and shrinking in the mantle which again produces the crustal shortening.

It is in the nature of the inductive process of investigation that each new body of evidence might force one to abandon cherished concepts. Such a new body of knowledge has been accumulating recently and can now no longer be ignored: the fault plane studies of earthquakes These studies are particularly important with respect to the physics of orogenesis since they give, at last, some direct evidence as to the mechanical behaviour of matter. Furthermore, there is also some new evidence as to the mechanical state of the material in the Earth's mantle. The latter turns out to be very similar to a "Kelvin body" as it exhibits elastic after-effects.

In the course of the analysis of this new evidence in the present paper, it will be seen that, in spite of the observed crustal shortening, most of the adjustments in earthquake-foci seem to be of a transcurrent nature. This is quite in contrast with what had been expected as it had always been thought that "normal" or reversed faulting would be the normal (hence the name) case. The occurrence of so much transcurrent faulting within

the mantle of the Earth presents a severe obstacle to acceptance of previously advanced theories of orogenesis as the latter were all based upon the sole occurrence of normal or reversed faulting. A renewed discussion of the possible mechanics is therefore necessary. From this it appears that there is seemingly no previously considered material which would entertain displacements as they are found in the Earth. It might, therefore, be necessary to postulate a new type of material not heretofore considered, unless it could be shown that a misinterpretation has occurred with the fault plane studies of earthquakes. In view of the fact that neither the stresses nor the temperatures prevalent in the mantle of the Earth have ever been duplicated in the laboratory, the postulate of a new mechanical material should not be too surprising. In any case, the ultimate understanding of orogenesis depends upon a proper understanding of the mechanics within the Earth's mantle; this has not yet been achieved.

II. Fault Plane Studies

Investigations into the mechanism of earthquakes were initiated some thirty years ago, but it has been only recently that such studies have been made on a sufficient number of earthquakes to permit world-wide effects to be recognized.

It is generally assumed that the cause of a seismic disturbance is confined to a relatively small region within the Earth's crust or mantle. This region is termed "focus" of the earthquake. Within the focus, a mechanical event must take place such as the sudden occurrence of failure of the material. Such a phenomenon would of necessity be connected with displacements within the focal region which, in turn, would cause seismic waves. The nature of the seismic waves originating from the focal region, therefore, should be an indication of the displacements occurring therein. In this instance, it cannot be expected, of course, that it will be possible to infer every detail of the focal mechanism from seismic waves, but rather the general behaviour of the focal region as a whole. As a first approximation, therefore, it seems reasonable to enclose the focal region within a sphere (termed "focal sphere") and to study the motion of the surface of this sphere as it may be inferred from seismic evidence. The size of the focal sphere must be such that it encloses the whole region of the focus in which mechanical deformation may have taken place during the earthquake, but that it is still small compared with the size of the whole Earth.

The various phases of a seismic disturbance that arrive at seismological observatories may be thought to have travelled along curved paths. The direction by which these phases leave the focal region can be calculated from travel-time tables. Thus, to each phase observed at any one seismic station corresponds a point on the focal sphere, viz. the point where the direction which the phase travelled when starting out from the focus intersects the focal sphere. If the motion near the focal region corresponding to each phase can be calculated from the observed motion at the station, the

geometrical change of the surface of the focal sphere during the occurrence of the earthquake considered can be inferred. Finally, it is a problem of mechanics to determine the possible failure patterns inside the focal sphere that might produce the observed displacements on its surface.

The problem is thus to determine, from seismic evidence, the displacement pattern of a sphere around the focus of an earthquake. The direction of displacement can be split into its radial and tangential components; at each point the radial component can be indicated by O (for "out") or Δ

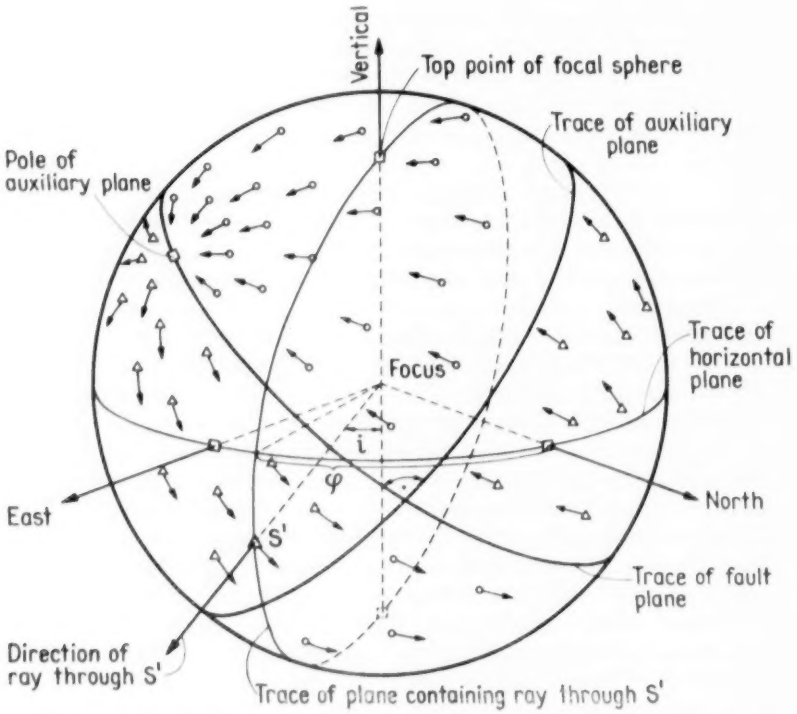

FIGURE 1.—The focal sphere (fault plane mechanism of earthquake generation).

(for "in"), and the direction of the tangential displacement can be plotted as an arrow (cf., e.g., Fig. 1). It is easy to show that the radial displacement of the focal sphere can be determined from P phases, whereas for the tangential displacements an analysis of S waves is necessary. It so happens that it is much easier to read P phases on seismograms than S phases, and therefore the direction of the radial displacement of the focal sphere can be obtained for many more points than the direction of the tangential displacement. In general, one has thus to be content with the knowledge of radial displacements only.

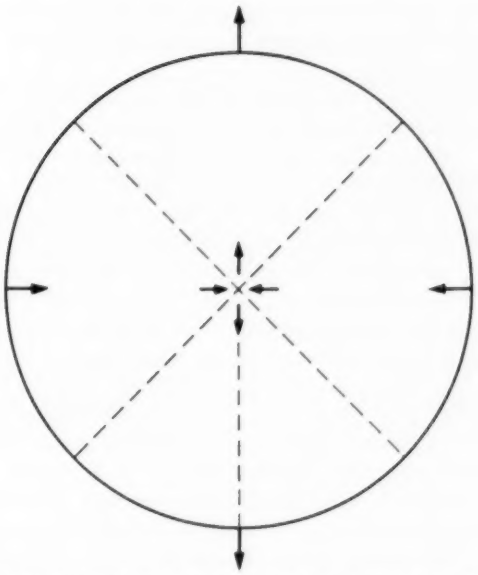

FIGURE 2.—The dipole mechanism of earthquake generation (after Nakano, 1923).

The interpretation of the radial displacement pattern of the focal sphere depends on the assumption of the true displacement pattern. Nakano (1923) has assumed the true displacement pattern to be of the multipole type. In practice, only a dipole displacement fits the actually observed patterns. In such a dipole displacement (see Fig. 2), the focal sphere appears as dissected by two orthogonal ("nodal") planes (containing the focus) into four quadrants which comprise alternately O and △ radial movements. The Japanese authors on the subject generally accept this mechanism as correct. However, it may be noted that the same radial displacement pattern of the focal sphere can also be obtained by assuming that a simple fault occurs in the focus. The total displacement is then as shown in Figure 1, the quadrants of O and △ radial movements again being engendered by two orthogonal planes (the "fault" plane and the "auxiliary" plane) through the focus. It appears to the present writer that the latter mechanism has more physical appeal than that accepted by the Japanese, particularly because the notion of the occurrence of a fault seems to be more in line with the fact that earthquakes appear as shocks. From P waves alone, it cannot be decided which is the fault plane and which is the auxiliary plane. In the dipole mechanism, such a distinction would not occur as the two nodal planes are equivalent orthogonal planes. In surface foci, the faults corresponding to one of the fault planes as determined from seismic data, have actually been observed (Hodgson, 1955a). This is a further indication that the interpretation of the seismic displacement pattern

in terms of faults is preferable to that in terms of nodal lines. The method of determining fault and auxiliary planes outlined above was originally initiated by Byerly (1938).

A large number of determinations of the position of the two orthogonal planes in the foci of earthquakes have been accumulated over the years. The early Japanese work has been summarized recently by Honda and Masatuka (1952), the Dutch work by Ritsema (1952). Some of this early work is, unfortunately, invalidated by the fact that, although it had always been recognized that the two planes engendering the quadrants on the focal sphere must be orthogonal, this property had not always been properly applied when the actual determination of the planes was carried out. Thus, in taking fault plane determinations from these sources, corrections had sometimes to be applied. Later on, many fault plane determinations were undertaken by Hodgson and co-workers (Hodgson, 1955a, b, c; Hodgson and Bremner, 1953; Hodgson and Milne, 1951; Hodgson and Storey, 1954) as well as by others (Adkins, 1940; Benioff *et al.* 1954; DiFilippo, 1950a, b; Vvedenskaya, 1951; Webb, 1954).

In Table I, we give a compilation of the results contained in the literature. If an earthquake has been investigated by more than one author, it has been entered repeatedly. It will be noted that in all such cases there is general agreement between the various authors as to the correct fault plane solution. In presenting the results, we have assumed that the fault plane idea represents the correct focal mechanism, hence two "fault plane solutions" are possible for each earthquake, denoted by (a) and (b), respectively. We give the dip direction and the dip for each solution, we state whether the fault is dextral (d) or sinistral (s), a tension (t) or a pressure (p) feature, and finally, we also give the angle between the motion-vector and the direction of strike (the "slip-angle"). The literature-reference for each solution is also given. The depth of each focus is given in terms of hundredths of the Earth's radius, according to Table II.

It should be noted that not all fault plane solutions are published in the literature as they are represented in our Table I. Apart from corrections which have been applied to satisfy the orthogonality condition as mentioned above, one also may use any desired three independent parameters to characterize each solution. In our Table 1, we give four parameters (dip direction and dip for each plane), but only three are independent. In the solutions published in the literature, any other three parameters may have been given from which ours had to be calculated, or else the solution may have been given in graph form (particularly in the Japanese work), and our parameters had to be measured.

It appears at once from Table I that most fault plane solutions of earthquakes represent chiefly transcurrent faulting. By the wording "chiefly transcurrent faulting" we mean that the angle between motion vector and strike direction (the "slip-angle") is smaller than the angle between motion vector and dip direction, i.e. smaller than 45°. To bear this out more

[*Text continues on p. 80.*]

TABLE I

TABLE OF FAULT PLANE DETERMINATIONS

Date and time	Epicentre	Depth (in O.OnR)	Solution	Dip direction	Dip	Slip angle	Fault type	Vertical compon.	Horiz. compon.	Refer.
Mch 7 1927	35.5°N	0.00	a	S61°W	64°	12°	sp			H55a
09:27:46	135.0°E		b							
Mch 7 1927	35.7°N	0.00	a	N60°E	90°	00°	s–	0.000	1.000	HM52
09:28	135.1°E		b	N30°W	90°	00°	d–	0.000	1.000	
Dec 10 1927	38° N	0.02	a	N45°W	90°	00°	d–	0.000	1.000	HM52
02:44	139.0°E		b	N°45°E	90°	00°	s–	0.000	1.000	
May 21 1929	31.8°N	0.00	a	N25°E	90°	00°	s–	0.000	1.000	HM52
16:35	131.8°E		b	N65°W	90°	00°	d–	0.000	1.000	
Mch 22 1930	35.0°N	0.00	a	N05°W	90°	00°	d–	0.000	1.000	HM52
08:50	139.1°E		b	N85°E	90°	00°	s–	0.000	1.000	
Oct 16 1930	36.3°N	0.00	a	N25°W	90°	00°	d–	0.000	1.000	HM52
21:36	136.3°E		b	N65°E	90°	00°	s–	0.000	1.000	
Nov 25 1930	35.1°N	0.00	a	N83°W	90°	00°	s–	0.000	1.000	HM52
19:03	139.0°E		b	N07°E	90°	00°	d–	0.000	1.000	
Dec 21 1930	34.8°N	0.00	a	N47°E	90°	00°	s–	0.000	1.000	HM52
12:14	132.9°E		b	N43°W	90°	00°	d–	0.000	1.000	
Jan 6 1931	42.4°N	0.01	a	N25°W	90°	90°	—	1.000	0.000	HM52
03:23	142.8°E		b	—	00°	—	—	0.000	1.000	
Jan 9 1931	39.8°N	0.02	a	S75°E	45°	90°	–p	0.707	0.707	HM52
01:46	140.6°E		b	N75°W	45°	90°	–p	0.707	0.707	
Feb 20 1931	44.5°N	0.05	a	S21°E	90°	42°	d–	0.669	0.743	HM52
05:34	135.7°E		b	N69°E	48°	90°	s–	0.000	1.000	
Apr 21 1931	38.5°N	0.05	a	N75°E	90°	00°	s–	0.000	1.000	HM52
00:03	134.2°E		b	N15°W	90°	00°	d–	0.000	1.000	
Jun 2 1931	36.0°N	0.03	a	N62°E	90°	39°	s–	0.629	0.777	HM52
02:28	137.5°E		b	N28°W	51°	00°	d–	0.000	1.000	
Jun 29 1931	34.2°N	0.05	a	S43°E	60°	19°	dp	0.326	0.946	HM52
16:43	136.5°E		b	S43°W	71°	30°	sp	0.500	0.866	
Aug 16 1931	30.9°N	0.00	a	N28°E	70°	23°	dp	0.375	0.927	B34
11:40:21	104.2°W		b	S55°E	68°	21°	sp	0.342	0.940	
Sep 21 1931	36.0°N	0.00	a	N15°E	90°	00°	s–	0.000	1.000	HM52
02:20	139.3°E		b	N75°W	90°	00°	d–	0.000	1.000	

TABLE I (*cont'd*)

TABLE OF FAULT PLANE DETERMINATIONS

Date and time	Epicenter	Depth (in O.OmR)	Solution	Dip direction	Dip	Slip angle	Fault type	Vertical compon.	Horiz. compon.	Refer.
Nov 2 1931	32.4°N	0.00	a	N15°E	90°	00°	s-	0.000	1.000	HM52
10:03	132.1°E		b	N75°W	90°	00°	d-	0.000	1.000	
Nov 3 1931	39.5°N	0.00	a	N45°E	90°	00°	d-	0.000	1.000	HM52
16:20	141.7°E		b	N45°W	90°	00°	s-	0.000	1.000	
Apr 4 1932	30.5°N	0.06	a	S20°E	37°	00°	d-	0.000	1.000	HM52
19:17	139.1°E		b	N70°E	90°	53°	s-	0.799	0.602	
Jul 25 1932	35.2°N	0.05	a	S03°E	60°	40°	st	0.552	0.834	HM52
08:25	135.9°E		b	N70°W	56°	37°	dt	0.500	0.866	
Sep 23 1932	44.7°N	0.05	a	S02°E	34°	00°	d-	0.000	1.000	HM52
14:23	139.0°E		b	N88°E	90°	56°	s-	0.829	0.559	
Nov 26 1932	42.4°N	0.00	a	N65°W	90°	00°	d-	0.000	1.000	HM52
04:24	142.3°E		b	N25°E	90°	00°	s-	0.000	1.000	
Dec 5 1932	33.7°N	0.05	a	N90°E	20°	90°	-p	0.342	0.940	HM52
00:20	137.0°E		b	N90°W	70°	90°	-p	0.940	0.342	
Mch 11 1933	26.5°N	0.07	a	N60°E	30°	90°	-t	0.866	0.500	HM52
19:33	140.5°E		b	S60°W	60°	90°	-t	0.500	0.866	
Sep 2 1933	30.3°N	0.05	a	S46°E	37°	30°	dt	0.225	0.974	HM52
16:42	139.4°E		b	N17°E	77°	58°	st	0.799	0.602	
Sep 21 1933	37.1°N	0.00	a	N05°W	90°	00°	d-	0.000	1.000	HM52
03:14	137.0°E		b	N85°E	90°	00°	s-	0.000	1.000	
Dec 4 1933	46.4°N	0.05	a	N76°E	90°	53°	s-	0.799	0.602	HM52
19:34	144.3°E		b	S14°E	37°	00°	d-	0.000	1.000	
Jul 6 1934	41.4°N	0.00	a	N50°E	84°	26°	dp	0.438	0.899	B38
22:48:56	125.4°W		b	S40°E	64°	06°	sp	0.104	0.994	
Aug 18 1934	35.7°N	0.00	a	N40°W	90°	00°	d-	0.000	1.000	HM52
02:38	137.0°E		b	N50°E	90°	00°	s-	0.000	1.000	
Apr 15 1935	36.2°N	0.04	a	S14°W	64°	36°	st	0.545	0.839	HM52
11:15	137.1°E		b	N60°W	57°	30°	dt	0.438	0.899	
May 31 1935	38.6°N	0.07	a	N65°E	64°	24°	st	0.407	0.914	HM52
08:19	134.2°E		b	S24°E	66°	26°	dt	0.438	0.899	

TABLE I (*cont'd*)

TABLE OF FAULT PLANE DETERMINATIONS

Date and time	Epicenter	Depth (in O.OnR)	Solution	Dip direction	Dip	Slip angle	Fault type	Vertical compon.	Horiz. compon.	Refer.
Jun 25 1936	32.5°N	0.05	a	N90°W	90°	58°	s–	0.848	0.530	HM52
16:52	137.9°E		b	S00°W	32°	00°	d–	0.000	1.000	
Oct 26 1936	34.5°N	0.05	a	N40°E	90°	90°	—	1.000	0.000	HM52
09:34	136.3°E		b	—	00°	—	—	0.000	1.000	
Dec 1 1936	30.7°N	0.04	a	N79°W	90°	49°	s–	0.755	0.656	HM52
06:10	129.0°E		b	N11°E	41°	00°	d–	0.000	1.000	
Apr 29 1937	45.7°N	0.05	a	S02°E	73°	00°	d–	0.000	1.000	HM52
20:20	137.3°E		b	N88°E	90°	17°	s–	0.292	0.956	
Jul 22 1937	64.7°N	0.00	a	S36°W	76°	22°	dt	0.375	0.927	A40
17:09:30	147.0°W		b	S55°E	68°	14°	st	0.242	0.970	
Aug 11 1937	06.5°S	0.09	a	N11°E	68°	61°	st	0.804	0.595	R52
00:55:56	116.5°E		b	S44°E	36°	40°	dt	0.366	0.930	
Jan 11 1938	33.7°N	0.00	a	N10°E	90°	00°	d–	0.000	1.000	HM52
15:12	135.2°E		b	N80°W	90°	00°	s–	0.000	1.000	
Feb 7 1938	36.3°N	0.01	a	N24°E	90°	22°	s–	0.375	0.927	HM52
14:43	139.2°E		b	S66°E	68°	00°	d–	0.000	1.000	
May 28 1938	43.6°N	0.00	a	N45°E	90°	00°	s–	0.000	1.000	HM52
16:42	144.3°E		b	N45°W	90°	00°	d–	0.000	1.000	
Apr 21 1939	47.6°N	0.08	a	S36°W	48°	43°	dt	0.500	0.866	HM52
04:30	140.2°E		b	S87°E	60°	51°	st	0.669	0.743	
May 1 1939	40.0°N	0.00	a	N35°W	90°	00°	d–	0.000	1.000	HM52
05:58	139.8°E		b	N55°E	90°	00°	s–	0.000	1.000	
Sep 22 1940	08.0°N	0.10	a	N53°E	54°	63°	dt	0.719	0.695	R52
22:51:57	124.0°E		b	N86°W	44°	58°	st	0.595	0.804	
Nov 26 1940	36.5°N	0.01	a	N80°E	90°	00°	d–	0.000	1.000	HM52
22:25	139.5°E		b	N10°W	90°	00°	s–	0.000	1.000	
Dec 30 1940	34.2°N	0.05	a	N50°E	85°	90°	–t	0.996	0.087	HM52
20:52	136.8°E		b	S50°W	05°	90°	–t	0.087	0.996	
Mch 16 1941	38.5°N	0.01	a	N68°E	90°	31°	d–	0.515	0.857	D50a
16:35:13	012.0°E		b	N22°W	59°	00°	s–	0.000	1.000	

TABLE I (*cont'd*)

TABLE OF FAULT PLANE DETERMINATIONS

Date and time	Epicenter	Depth (in O.OnR)	Solution	Dip direction	Dip	Slip angle	Fault type	Vertical compon.	Horiz. compon.	Refer.
Apr 11 1941	31.7°N	0.03	a	N85°W	90°	90°	—	1.000	0.000	HM52
15:37	137.8°E		b	—	00°	—	—	0.000	1.000	
Jul 15 1941	36.7°N	0.00	a	N34°E	90°	00°	s-	0.000	1.000	HM52
14:45	138.2°E		b	N56°W	90°	00°	d-	0.000	1.000	
Nov 25 1941	37.3°N	0.00	a	N87°E	70°	00°	s-	0.000	1.000	D50b
18:03:55	019.0°W		b	N03°W	90°	20°	d-	0.334	0.943	
Apr 20 1942	33.9°N	0.05	a	N80°W	90°	90°	—	1.000	0.000	HM52
08:41	137.3°E		b	—	00°	—	—	0.000	1.000	
Mch 4 1943	35.6°N	0.00	a	N73°E	90°	00°	s-	0.000	1.000	HM52
10:13	134.2°E		b	N17°W	90°	00°	d-	0.000	1.000	
Mch 4 1943	35.6°N	0.00	a	N23°W	90°	00°	d-	0.000	1.000	HM52
19:50	134.2°E		b	N67°E	90°	00°	s-	0.000	1.000	
Aug 12 1943	37.3°N	0.00	a	N38°E	90°	00°	s-	0.000	1.000	HM52
04:50	139.8°E		b	N52°W	90°	00°	d-	0.000	1.000	
Sep 10 1943	35.5°N	0.00	a	N22°W	90°	00°	d-	0.000	1.000	HM52
08:37	134.2°E		b	N68°E	90°	00°	s-	0.000	1.000	
Oct 13 1943	36.8°N	0.00	a	N18°E	90°	00°	d-	0.000	1.000	HM52
05:42	138.2°E		b	N72°W	90°	00°	s-	0.000	1.000	
Nov 17 1943	33.0°N	0.05	a	S00°W	33°	00°	d-	0.000	1.000	HM52
14:58	138.0°E		b	N90°W	90°	57°	s-	0.839	0.545	
Apr 1 1946	53.5°N	0.00	a	N25°E	65°	06°	dt	0.087	0.996	HM51
12:28:58	163.0°W		b	N68°W	85°	25°	st	0.423	0.906	
Jun 23 1946	49.9°N	0.00	a	N67°E	60°	60°	dt	0.848	0.530	HM51
17:13:20	124.9°W		b	N89°W	33°	38°	st	0.500	0.866	
Nov 4 1946	39.8°N	0.00	a	N69°W	57°	90°	-t	0.839	0.545	V51
21:47:47	54.5°E		b	S69°E	33°	90°	-t	0.545	0.839	
Nov 10 1946	08.0°S	0.00	a	N45°E	71°	29°	sp	0.462	0.887	HB53
	078.0°W		b	N55°W	62°	21°	dp	0.326	0.946	
Feb 18 1947	33.0°N	0.06	a	S18°W	31°	00°	d-	0.000	1.000	HM52
12:31	136.8°E		b	N72°W	90°	59°	s-	0.852	0.515	
Oct 16 1947	64.0°N	0.00	a	N60°E	78°	90°	-t	0.978	0.208	HM51
02:09:07	148.0°W		b	S60°W	12°	90°	-t	0.208	0.978	

TABLE I (*cont'd*)

TABLE OF FAULT PLANE DETERMINATIONS

Date and time	Epicenter	Depth (in O.OnR)	Solution	Dip direction	Dip	Slip angle	Fault type	Vertical compon.	Horiz. compon.	Refer.
Jun 28 1948	36.1°N	0.00	a	N78°E	90°	00°	s-	0.000	1.000	HM52
07:13	136.2°E		b	N12°W	90°	00°	d-	0.000	1.000	
Jun 29 1948	16.0°S	0.01	a	N43°W	86°	05°	dp	0.087	0.996	W54
10:28:42	172.9°W		b	N48°E	85°	04°	sp	0.070	0.998	
Sep 8 1948	21.0°S	0.00	a	S62°E	87°	42°	dp	0.669	0.743	W54
15:09:14	174.2°W		b	S31°W	48°	04°	sp	0.052	0.999	
Dec 30 1948	51.0°N	0.00	a	N25°E	39°	38°	st	0.391	0.920	HS54
23:50	131.0°W		b	S34°E	67°	58°	dt	0.771	0.629	
Jan 20 1949	35.6°N	0.00	a	N85°N	90°	00°	s-	0.000	1.000	HM52
13:25	134.6°E		b	N05°W	90°	00°	d-	0.000	1.000	
Mch 4 1949	37.0°N	0.03	a	N04°W	87°		-t			HS54
	070.0°E		b							
Apr 5 1949	43.0°N	0.08	a	N23°W	64°	35°	dp	0.500	0.866	HS54
09:27	131.0°E		b	N84°E	60°	32°	sp	0.438	0.899	
Apr 5 1949	42.0°N	0.09	a	N22°W	90°	00°	d-	0.000	1.000	HM52
09:28	131.0°E		b	N68°E	90°	00°	s-	0.000	1.000	
Apr 13 1949	47.0°N	0.00	a	N41°W	83°	80°	sp	0.978	0.208	HS54
19:55:41	122.6°W		b	S14°W	12°	36°	dp	0.122	0.992	
Apr 20 1949	38.0°S	0.01	a	N53°E	90°	00°	d-	0.000	1.000	HS54
03:29:00	072.5°W		b	N37°W	90°	00°	s-	0.000	1.000	
May 3 1949	49.0°N	0.01	a	S84°W	75°	19°	dp	0.326	0.946	HS54
05:57	153.0°E		b	N01°W	71°	15°	sp	0.259	0.966	
May 8 1949	20.0°S	0.01	a	N22°E	78°	90°	-p			HS54
	071.0°W									
Jun 12 1949	27.0°S	0.09	a	N90°W	90°	00°	d-	0.000	1.000	HS54
	064.0°W		b	N00°W	90°	00°	s-	0.000	1.000	
Jul 10 1949	39.0°N	0.00	a	N19°W	76°	90°	-t			HS54
	071.0°E									
Jul 11 1949	34.0°N	0.00	a	N73°W	90°	00°	s-	0.000	1.000	HM52
16:10	132.5°E		b	N17°E	90°	00°	d-	0.000	1.000	
Jul 23 1949	18.5°S	0.03	a	S50°W	85°	23°	sp	0.391	0.920	HS54
10:25:49	169.0°E		b	S41°E	67°	05°	dp	0.087	0.996	

TABLE I (*cont'd*)

TABLE OF FAULT PLANE DETERMINATIONS

Date and time	Epicenter	Depth (in O.On.R)	Solution	Dip direction	Dip	Slip angle	Fault type	Vertical compon.	Horiz. compon.	Refer.
Aug 5 1949	01.0°S	0.00	a	N08°W	66°	14°	st	0.225	0.974	HS54
19:08:47	078.0°W		b	N88°E	77°	25°	dt	0.407	0.913	
Aug 22 1949	54.1°N	0.00	a	N61°E	77°	18°	dp	0.309	0.951	HM51
04:01:09	132.6°W		b	S26°E	72°	13°	sp	0.225	0.974	
Sep 27 1949	60.0°N	0.00	a	N20°E	72°	90°	-t			HS54
15:30:43	149.0°W									
Nov 3 1949	48.0°N	0.03	a	N23°E	77°	11°	st	0.191	0.982	HS54
01:12:37	154.0°E		b	S65°W	79°	13°	dt	0.225	0.974	
Nov 22 1949	29.0°S	0.00	a	N40°W	86°	02°	dp	0.035	0.999	HS54
00:51:32	178.0°W		b	N50°E	88°	04°	sp	0.070	0.996	
May 17 1950	21.0°S	0.00	a	N86°W	79°	20°	dp	0.326	0.946	H55b
18:13:13	169.0°E		b	N08°E	71°	12°	sp	0.191	0.982	
May 19 1950	20.5°S	0.00	a	N58°W	84°	19°	dp	0.331	0.943	H55b
02:38:10	169.0°E		b	N34°E	71°	06°	sp	0.110	0.994	
May 19 1950	20.5°S	0.00	a	N88°W	84°	14°	dp	0.259	0.966	H55b
07:05:10	169.0°E		b	N04°E	76°	06°	sp	0.104	0.994	
May 26 1950	20.2°S	0.00	a	N80°W	73°	18°	dp	0.292	0.956	H55b
01:17:25	169.2°E		b	N16°E	73°	18°	sp	0.292	0.956	
May 27 1950	20.0°S	0.00	a	S67°W	86°	03°	st	0.052	0.999	H55b
12:39:43	168.0°E		b	N23°W	87°	04°	dt	0.070	0.998	
May 28 1950	20.0°S	0.00	a	N43°W	68°	00°	d-	0.000	1.000	H55b
01:36:44	169.0°E		b	N47°E	90°	00°	s-	0.375	0.927	
Jun 21 1950	20.2°S	0.00	a	N80°W	77°	20°	dp	0.342	0.940	H55b
06:55:37	169.5°E		b	N14°E	70°	14°	sp	0.225	0.974	
Jun 24 1950	20.5°S	0.00	a	S86°W	81°	18°	dp	0.309	0.951	H55b
22:25:24	169.5°E		b	N02°W	72°	09°	sp	0.156	0.988	
Jul 17 1950	20.5°S	0.01	a	S60°W	87°	12°	dp	0.208	0.978	H55b
20:17:50	171.0°E		b	N30°W	78°	03°	sp	0.052	0.999	
Jul 21 1950	15.5°S	0.00	a	N19°E	72°	60°	dp	0.819	0.574	H55b
20:32:01	168.5°E		b	S43°E	35°	33°	sp	0.309	0.951	
Jul 22 1950	14.0°S	0.00	a	N57°E	89°	14°	sp	0.242	0.970	H55b
23:08:00	167.0°E		b	N33°W	76°	01°	dp	0.017	1.000	

TABLE I (*cont'd*)

TABLE OF FAULT PLANE DETERMINATIONS

Date and time	Epicenter	Depth (in O.On R)	Solution	Dip direction	Dip	Slip angle	Fault type	Vertical compon.	Horiz. compon.	Refer.
Sep 10 1950	15.5°S	0.01	a	S84°E	64°	07°	sp	0.208	0.978	H55b
15:16:08	167.0°E		b	N04°E	78°	29°	dp	0.430	0.903	
Dec 2 1950	18.2°S	0.05	a	S46°W	88°	04°	sp	0.067	0.998	W54
19:51:52	167.0°E		b	S45°E	86°	02°	dp	0.035	0.999	
Feb 13 1951	15.0°S	0.03	a	S58°W	88°	04°	dp	0.070	0.998	H55b
11:55:50	175.0°W		b	N32°W	86°	02°	sp	0.035	0.999	
Mar 10 1951	15.3°S	0.02	a	N49°W	84°	09°	st	0.156	0.988	W54
21:57:37	167.5°E		b	N42°E	81°	06°	dt	0.104	0.994	
Mar 23 1951	31.0°S	0.04	a	N57°W	86°	25°	dt	0.423	0.906	H55b
21:38:54	180.0°E		b	S31°W	65°	04°	st	0.070	0.998	
Aug 28 1951	27.0°S	0.09	a	N42°W	87°	03°	st	0.052	0.999	H55b
16:31:11	178.0°E		b	N48°E	87°	03°	dt	0.052	0.999	
Feb 25 1952	17.0°S	0.00	a	N52°W	87°	18°	st	0.309	0.951	H55b
01:17:00	173.5°W		b	N38°E	72°	03°	dt	0.052	0.999	
May 9 1952	06.5°S	0.01	a	S52°E	56°	22°	sp	0.309	0.559	H55b
17:47:40	155.0°E		b	N26°E	72°	36°	dp	0.559	0.829	
Jul 13 1952	18.5°S	0.05	a	S74°E	70°	22°	sp	0.358	0.934	H55b
11:58:34	169.5°E		b	N09°E	69°	21°	dp	0.342	0.940	
Jul 21 1952	35.0°N	0.00	a	S40°E	63°	68°	sp	0.809	0.588	BGR54
11:52:14	119.0°W		b	N00°W	36°	55°	dp	0.454	0.891	
Jul 27 1952	20.5°S	0.07	a	N73°W	88°	28°	dp	0.470	0.883	H55b
08:23:22	179.0°W		b	N17°E	62°	02°	sp	0.035	0.999	
Sep 11 1952	29.0°S	0.00	a	N57°W	90°	06°	s–	0.104	0.994	H55b
22:26:41	177.0°W		b	N33°E	84°	00°	d–	0.000	1.000	
Jul 2 1953	18.5°S	0.03	a	indetermined						H55b
06:56:51	169.0°E		b	S24°W	87°					
Sep 14 1953	18.5°S	0.00	a	N29°W	83°	02°	st	0.035	0.999	H55b
00:26:36	178.5°E		b	N61°E	88°	07°	dt	0.122	0.992	
Sep 29 1953	36.5°S	0.04	a	S36°E	87°	01°	dp	0.018	1.000	H55b
01:36:45	177.0°E		b	S54°W	89°	03°	sp	0.052	0.999	
Jan 13 1954	49.0°S	0.00	a	S46°E	86°	09°	sp	0.156	0.988	H55b
00:13:06	165.0°E		b	S44°W	81°	04°	sp	0.070	0.998	

CHART 1.—Map showing fault planes in earthquakes in western Eurasia. Deep earthquakes are represented by double lines, shallow ones by single lines. Arrows pointing away from each other (as in the earthquake at the Caspian Sea) indicate a tensional dip-slip fault (i.e., a "normal" fault); half-arrows (as in the earthquake near Sicily) indicate transcurrent faults—in this case the arrows point in the direction of strike. Because of the ambiguity of the fault plane technique there are usually two possibilities for the focal fault. If these two possibilities are plotted on top of each other, a starlike figure (as in the earthquake near Sicily) results.

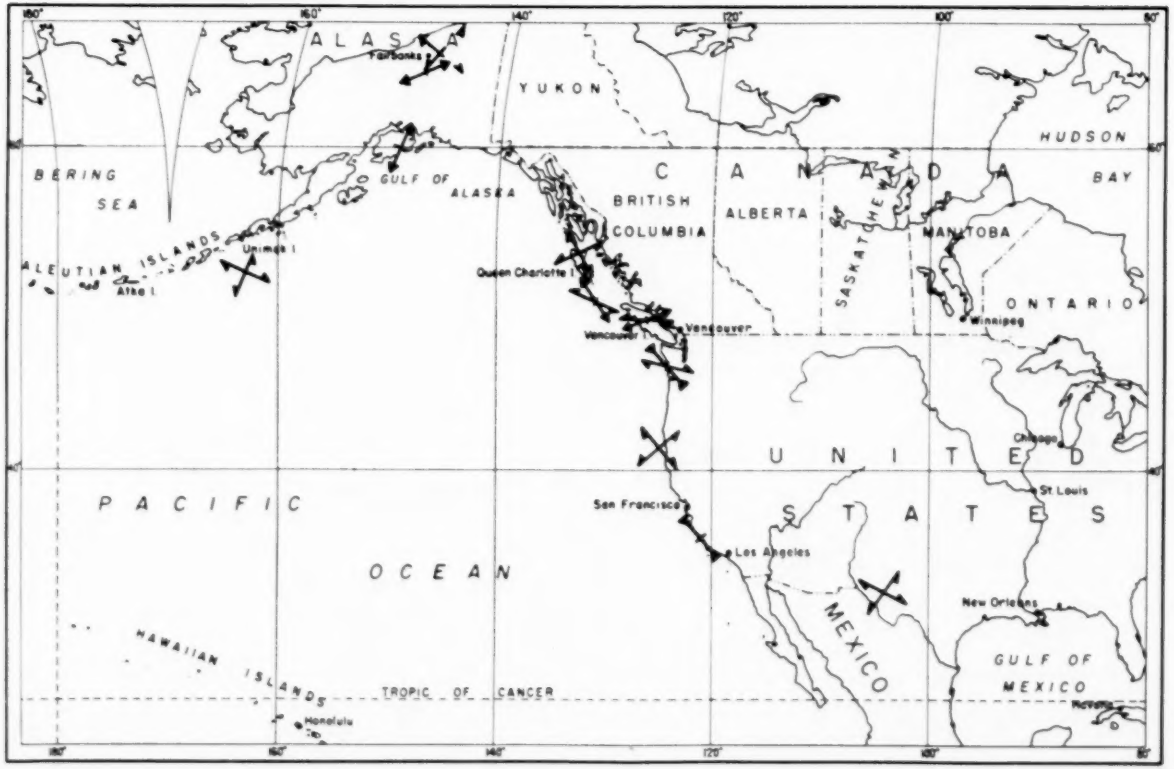

CHART 2.—Map showing fault planes in earthquakes in the north-east Pacific Ocean.

CHART 3.—Map showing fault planes in earthquakes in South America.

clearly, the earthquakes have also been plotted on charts (see Charts 1–7). If the faulting was chiefly transcurrent (i.e., the slip angle less than 45°), the motion has been plotted by two half-arrows along the strike direction (cf., e.g., Mediterranean earthquake on Chart 1), if it was normal or reversed (slip angle larger than 45°), the arrows point in the dip direction:

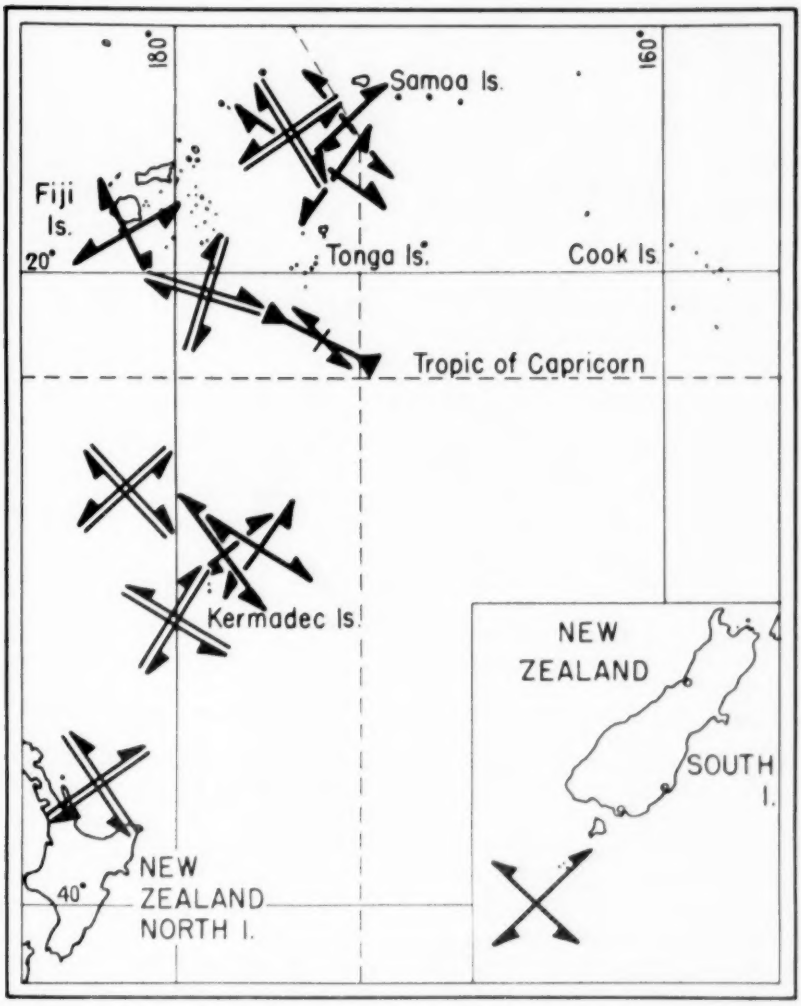

CHART 4.—Map showing fault planes in earthquakes in the southwest Pacific Ocean.

towards each other for a pressure feature, away from each other for a tension feature (cf., e.g., for tension feature, earthquake near Caspian Sea on Chart 1). Sometimes, the motion is vertical so that one cannot distinguish between pressure and tension feature. In this case, circles have been used instead of arrowheads. The earthquakes represented by single lines have a focal depth smaller than or equal to 0.01R, the deeper ones are represented by double lines.

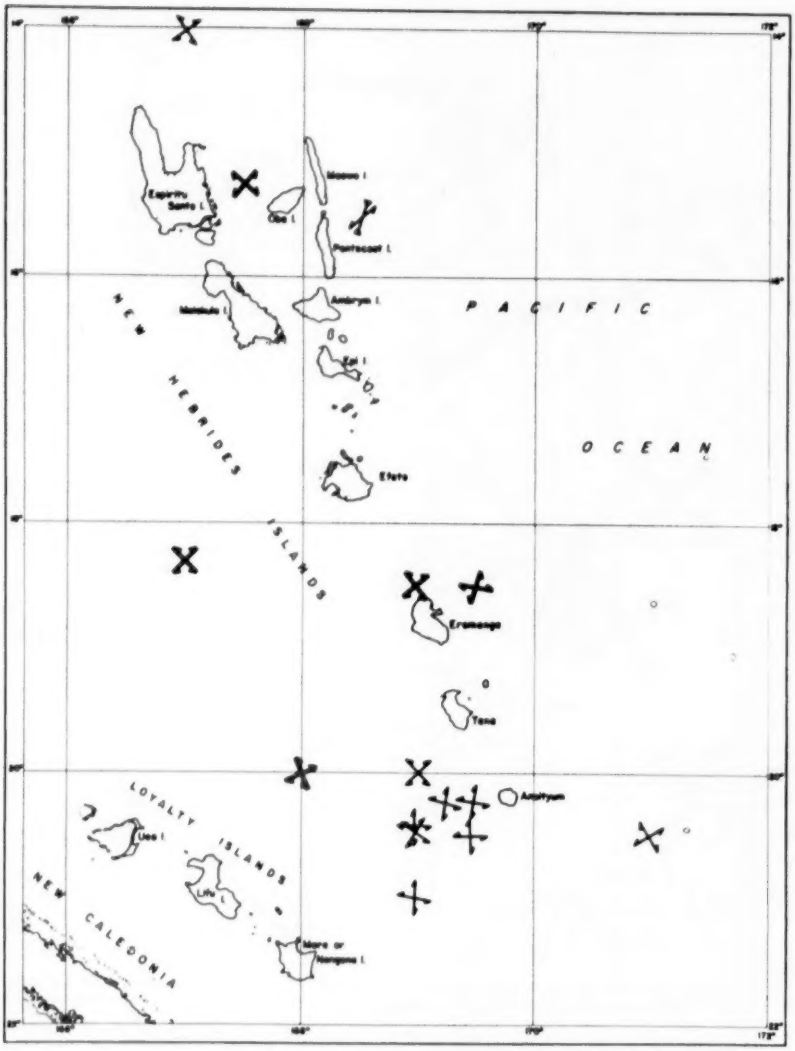

CHART 5.—Map showing fault planes in earthquakes in the New Hebrides Islands area.

Upon inspection of the charts, it becomes at once apparent that the faulting is chiefly transcurrent everywhere and at all depths.

With the data contained in Table I one can do some statistical analysing. Out of 110 earthquakes, representing 218 possible fault planes, (in two earthquakes it is known which is the fault and which is the auxiliary plane), 171 fault planes represent transcurrent faulting, and only 43 normal or

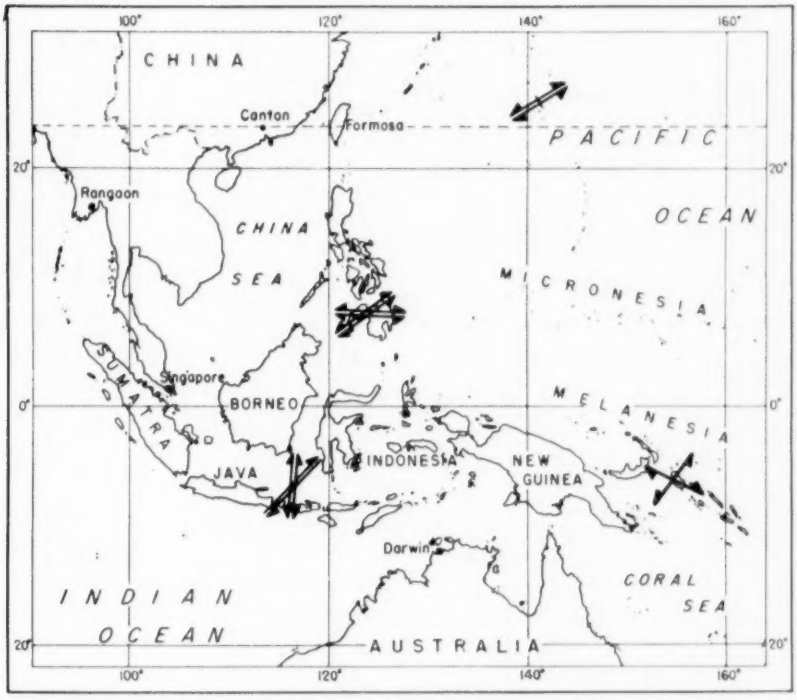

CHART 6.—Map showing fault planes in earthquakes in the Eastern Archipelago.

reversed faulting. The remaining 4 fault planes do not fit either category. This means that 78 per cent of the fault plane solutions represent transcurrent faulting, and only 20 per cent normal or reversed faulting; the remaining 2 per cent do not fit either category. These percentage figures, however, should not be taken as an indicator of the exact proportion of transcurrent and normal-reversed faulting in *all* earthquakes. It is a fact that it is easier to obtain a fault plane solution for an earthquake featuring transcurrent motion than for an earthquake featuring normal-reversed motion. Nevertheless, even if the above percentage figures tend to be biased in favour of transcurrent earthquakes, they still demonstrate that transcurrent faulting in earthquake foci is certainly a major feature which cannot be neglected.

A quantitative account of the large amount of horizontal adjustment which is apparently found in earthquake motions, may be obtained by calculating the components of vertical and of horizontal motion in all earthquakes listed in Table I. Hence, two columns are appended in Table I giving these values.

One can now calculate the average horizontal and vertical displacements in, say, all depth zones engendered by steps of 0.01R. For a comparison of

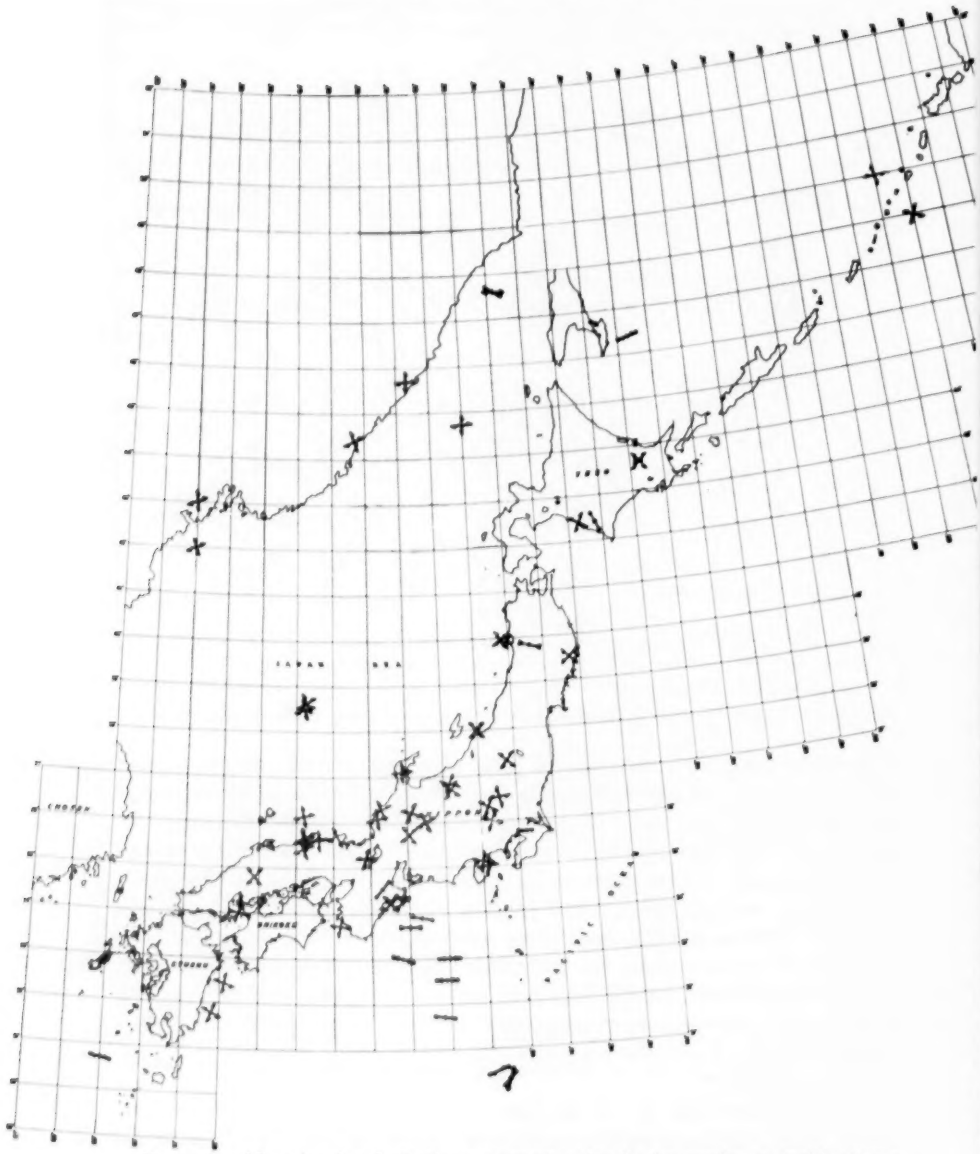

CHART 7.—Map showing fault planes in earthquakes in the northwest Pacific Ocean.

the values of horizontal and vertical adjustments, one should observe that there is only one vertical dimension, but that there are two horizontal ones. It is pure chance what angle the particular horizontal direction of adjustment in any one earthquake makes with a fixed horizontal direction. Since

TABLE II

DEPTH OF FOCI OF EARTHQUAKES IN KILOMETERS AND O.On R

Km.	O.OnR
0	Surface
33	0.00
96	0.01
160	0.02
223	0.03
287	0.04
350	0.05
413	0.06
477	0.07
540	0.08
603	0.09
667	0.10
730	0.11
794	0.12

only that component of the horizontal motion of the earthquake is significant which falls into the considered horizontal direction, one has to multiply the value for the earthquake displacement by the cosine of the angle between the latter and the considered horizontal direction. This angle, however, may be anything between 00° and 90° and therefore, on the average, the horizontal earthquake motion values must be multiplied by the mean of the cosine between 00° and 90°, i.e., by $2/\pi$. In Table III, we give, therefore, for each depth region (in steps of 0.01R), the ratio of total average horizontal displacement and the average vertical displacement. Furthermore, it might be interesting to see the distribution of pressure vs. tension features in the various depth categories. This information, also, has been supplied in Table III.

TABLE III

Depth (in O.OnR)	No. of earthquakes	Per cent tension	Per cent compression	Per cent indet.	Average ratio hor./vert. comp.	Average mot. angle w. horiz.
0.00R	56	20	32	48	3.45	16°
0.01R	11	0	55	45	2.65	21°
0.02R	3	33	33	34	2.05	26°
0.03R	8	25	38	37	2.47	22°
0.04R	4	50	25	25	2.02	26°
0.05R	16	19	25	56	1.30	38°
0.06R	2	0	0	100	1.20	39°
0.07R	3	67	33	0	1.19	40°
0.08R	2	50	50	0	1.02	44°
0.09R	4	50	0	50	3.77	15°
0.10R	1	100	0	0	0.74	53°

III. The Physics of Orogenesis

We come now to analyse the physics of orogenesis in the light of new seismological information. This information stems partly from the fault plane studies mentioned in the last section, and partly from earlier studies. It may be summarized as follows:

(*a*) Earthquakes appear to occur in localized zones which are almost planar, dipping at some intermediate angle (30°–60°) into the Earth (see Fig. 3). The fact that earthquakes are distributed in such a fashion has been shown by Gutenberg and Richter (1949).

(*b*) Earthquakes represent actual fractures, i.e., sudden releases of stress. Thus, the material of the orogenetic shell must be capable of fracturing. Furthermore, the aftershock sequences of large earthquakes (Benioff, 1951) suggest that the stress-strain relationship of the material in the Earth's mantle shows the phenomenon of an elastic aftereffect; i.e., the rheological equation of state corresponds to that of a body which Reiner (1949) calls a "Kelvin-body."

(*c*) The fracturing of the mantle is mostly transcurrent, i.e. *not* parallel to the dip of the planar earthquake zones mentioned under (*a*). One of the chief difficulties presented by this observation is that of making the large transcurrent component of earthquake-motions compatible with the obviously encountered crustal shortening which is evidenced by the upthrust of mountains, as well as with the existence of the planar earthquake zones. No matter which theory of orogenesis is considered, this crustal shortening has always been considered basic. If this were correct, then the

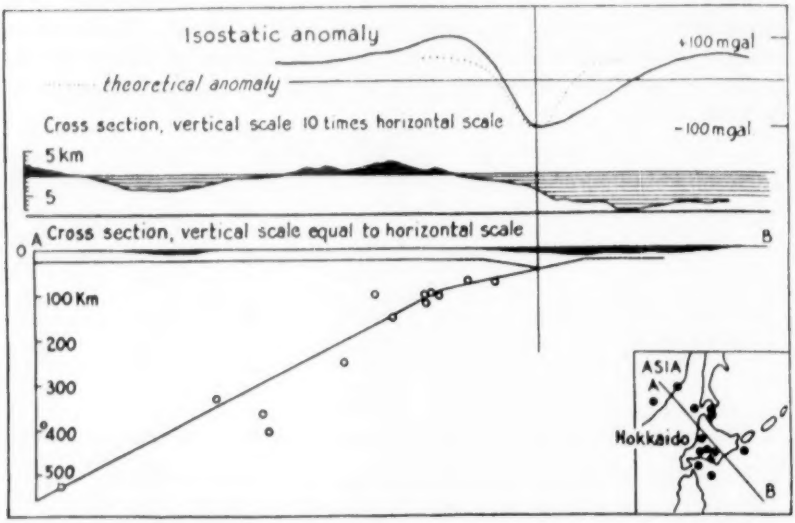

FIGURE 3.—Gravity anomalies and vertical distribution of the foci of deep earthquakes (after Gutenberg and Richter, 1949).

faulting occurring during earthquakes should be either normal or reversed, but certainly not transcurrent. Therefore, one is faced with the problem of having to understand how a stress system in some material can possibly produce "crustal shortening" at the surface of that material and transcurrent adjustments within its interior.

The only way to deal with the problem appears to be a renewed discussion of the possible mechanical behaviour of materials similar to that in an earlier paper of the writer (Scheidegger, 1953)—but this time with special reference to the new seismological evidence. At the outset, we shall an earlier paper of the writer (Scheidegger, 1953)—but this time with the new evidence, and later we shall discuss possible modifications thereof.

Turning first to the possibility of orogenesis by flow and its compatibility with seismology, it must be observed from the outset that flow, itself, is *not* compatible with the notion of earthquakes; for flow is a slow, steady phenomenon (at least in those forms considered as possibly pertinent to orogenesis) which does not feature any shock-like displacements such as occur in earthquakes. If a flow phenomenon is the cause of orogenesis, then it must take place well below the region in which earthquakes occur, or else it must be such a slow flow that the sudden release of stresses represented by earthquakes can be superimposed upon it. The theory of orogenesis based upon a flow phenomenon which is commonly considered, is the convection current theory. In that theory (cf. Griggs, 1939; Vening Meinesz, 1947), convection currents in the mantle are supposed to rotate near the edges of continents, thus accumulating material at the latter which is folded up in the form of islands and mountains. The authors of the convection current theory were well aware of the difficulty of the existence of deep-focus earthquakes, and proposed therefore that the convection currents be much slower than the period of occurrence of earthquakes, which would permit short-term stress releases (cf. Fig. 4). The present author has shown (Scheidegger, 1952) that such a mechanism appears indeed as compatible with the mechanics of continuous matter.

However, convection currents as proposed by various authors represent a phenomenon which takes place, essentially, in a vertical plane. The arcuate strike of island arcs is therefore not explainable, and, in addition, all the differential displacements take place in a vertical plane (Fig. 4). The fact that most earthquakes are the outcome of transcurrent dislocations (i.e. horizontal differential displacements) is therefore at variance with theory. The only exit from this dilemma would be if the currents would rotate in a horizontal plane like giant vortices: this rotation would produce the required horizontal differential displacements. However, nobody has as yet suggested the existence of horizontal vortices in the Earth's mantle as such a proposition would obviously be incompatible with the physiographic appearance of the Earth's surface. It therefore appears that the convection current theory, in its commonly accepted form at least, is not compatible with large transcurrent adjustments.

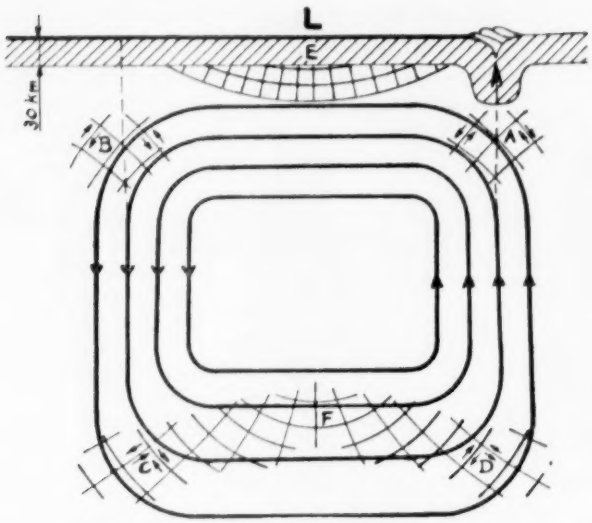

FIGURE 4.—Convection currents and areas of sliding fracture (after Vening Meinesz, 1947).

We turn now to the second group of theories of orogenesis, which are at present in the literature considered as possibly correct, viz. theories based upon the failure of materials. These theories are based upon the hypothesis of contraction of the Earth's interior. This hypothesis assumes that the Earth has been a hot, liquid celestial body at one stage of its life. It solidified quickly and continued to cool by radiation. The theory is that the silicate mantle solidified from its base at the top of the liquid metallic core outward and has since been cooling by conduction without convection currents. From the centre of the Earth to within about 700 km. of the surface, there has not been time since the Earth solidified for any appreciable cooling nor for any significant change in volume to have taken place. Within the region from about 700 to 100 km. depth, cooling by conduction is taking place and hence this shell is contracting and being stretched about the unchanging interior. Hence it is in a state of internal tension. This layer is the orogenetic shell. Near the surface, the rocks have already cooled so that they are not changing in volume and the cooling and contraction in the layer below puts them into a state of compression. In between the shell under tension and that under compression there must be assumed a level of no strain.

The geological implications of the contraction theory have been followed up by Wilson (1951, 1954) to obtain a coherent theory of growth of terrestrial features. He showed that the geology, the volcanism, and the whole pattern of existing mountain ranges can be explained in terms of this theory. In particular, a stage of orogenetic activity would consist of a process which is most eloquently explained by the drawing shown in Fig. 5.

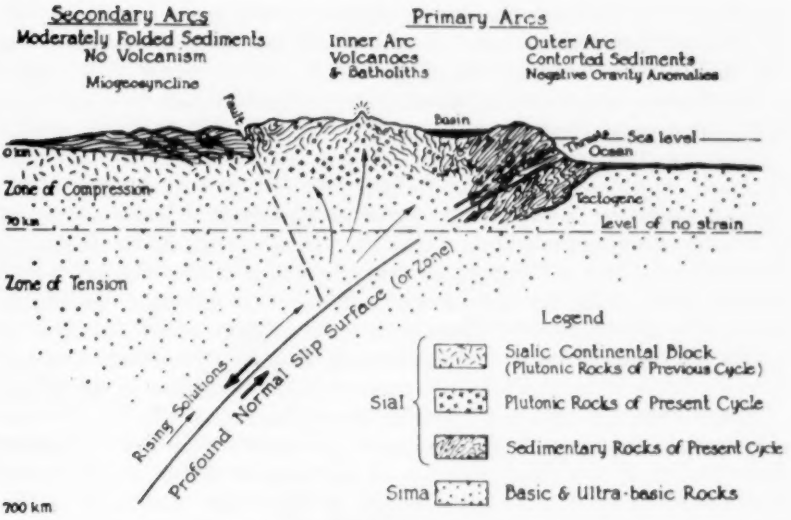

FIGURE 5.—Wilson's theory of mountain ranges and island arcs (after Wilson, 1951).

From this drawing (Fig. 5) it is again apparent that, in the present form of the contraction theory, there is no room for any transcurrent adjustments at all. In this sense, it must be held that the present contraction theory also is not compatible with the seismic evidence summarized in section II of the present paper. Furthermore, although there is a definite indication that thrust is preponderant in depths up to 0.01R, there is no definite confirmation of the assumption of a level of no strain at 0.01R nor of the preponderance of tension at depths below 0.01R (see Table III).

The situation is therefore that *none* of the present theories of orogenesis is compatible with the new seismological data. One will therefore have to look for modifications of these theories or for a new theory altogether. In doing so, it must be well understood that the observed transcurrent motion is certainly not a minor effect which could be disposed of lightly by the assumption of "local" irregularities in the Earth's crust. The transcurrent faulting is obviously, from the data presented in section II, a world-wide effect which must play a major role in any correct theory of orogenesis.

All the present theories of orogenesis, as has been indicated above, assume stress systems that cause "crustal shortening." In fact, such crustal shortening is essentially a horizontal displacement. It has usually been considered that this displacement has been produced by a system of normal or reversed faults. The latter all have a significant vertical component. From an *a priori* standpoint it appears remarkable that nobody has ever thought to

produce the final horizontal displacements (i.e., the crustal shortening) by a system of displacements which do not possess any vertical components at all, viz. by transcurrent faults. Logically, it would appear much more straightforward to obtain the required large horizontal shifts by a system of purely horizontal displacements than by displacements which do possess vertical components as well. The reason for this not having been thought of before, of course, is that it is difficult to envisage a mechanism which operates essentially in a horizontal direction. Furthermore, the arrangement of earthquakes in a plane dipping into the Earth (according to Gutenberg and Richter, 1949; see Fig. 3) naturally suggested that something would happen in which this plane would be important. It is thus most remarkable that earthquake motions do have a large component which does not lie within that plane. Thus, convection as well as contraction theories started from the faulty assumption that the motions would take place in this plane.

Nevertheless, this obliquely dipping plane *does* exist (cf. Fig. 3) and introduces an additional obstacle to finding a sensible theory of orogenesis. The existence of this plane demands an explanation, and it is hard to see how a mechanism can be found which produces that plane and at the same time also produces differential displacements in a direction which does not seem to have any simple geometric relationship with that plane.

It is difficult to think of a way out of this dilemma. Of the various mechanical bodies, none seems to fit the mechanical behaviour of the orogenetic shell. The writer fails to see how any type of vertical thermal convection currents could produce horizontal differential displacements. If currents are the cause of orogenesis, they must themselves be essentially horizontal, which appears incompatible with the physiographic appearance of the Earth's surface.

Turning next to the possibility of orogenesis by rheological flow, one might think first that some form of the theory of plastic materials might be the solution. Indeed, it is well known that in a rigid-plastic material which is being stressed above its yield point, zones of plastic deformations are being formed. The shearing deformation in the plastic zones is along slip lines which are not parallel to the boundaries of the plastic region. One thus has a theory where the direction of slip and the boundaries of the slip areas do not have a simple geometrical correlation. This would enable one to identify the zone of plastic deformation with the obliquely dipping earthquake zone, and the slip surface with the fault planes of earthquakes. However, it should be noted that the theory of plasticity is one of steady or quasi-static deformation. It is therefore difficult to see how the slip along slip lines could give rise to the shock-like adjustments which earthquakes represent. Furthermore, most known plastic materials show the effect of strain-hardening which means that an ever increasing force has to be applied to maintain a certain rate of deformation. This is in contrast with the experience of earthquakes where a small deformation instantaneously seems to grow into a large one representing a shock.

It thus appears that there is no way around the fact that earthquakes represent an actual rupture or fracture of the material, and that the second group of theories of orogenesis is thus strongly favoured. However, there is no theory of rupture known to the writer where the displacements are not parallel to the zone of rupture. Perhaps it would be possible to describe the effect by the assumption of a new mechanical material which would be something like a rigid-plastic body, but would show the effect of "strain-weakening" rather than the strain-hardening commonly encountered. At any rate, it would have to be a body which, first, can develop a zone of weakness corresponding to the planar arrangement of the earthquakes with depth; which, secondly, shows elastic after-effects; and, thirdly, which can show fractures within a zone of weakness along planes which have no simple geometrical relationship with the boundary of the zone of weakness. The fact that no such material has been encountered heretofore should not be too surprising, as it may well be connected with the condition that stresses and temperature in the orogenetic shell must be vastly different from those encountered in the laboratory.

IV. Conclusion

In view of the expositions contained in this paper, it appears that the phenomenology of the mechanical behaviour of the Earth's mantle with respect to short-term displacements, such as earthquakes, is now fairly well established.

The main features of the displacements within the mantle are, first, that they are localized in almost planar zones dipping at some intermediate angle beneath recent mountain and island belts; secondly, that the stress-strain relationship of the material involved exhibits an elastic after-effect; and, thirdly, that the differential displacements are to a large extent horizontal, i.e. *not* parallel to the dipping planar zones.

The fact that earthquakes appear as shocks strongly suggests the assumption that they are the outcome of a fracture-like phenomenon, and not of a flow-process. This presents a great difficulty in accepting as an explanation any theory based on crustal currents, as well as the theory of plasticity, for the latter describes motions which are quasi-static. On the other hand, there are no theories of fracture known to the writer in which the direction of the differential displacements would not coincide with the surface of rupture.

It is thus almost apparent that the mechanical behaviour of the Earth's mantle corresponds to that of a material of which there has been no example encountered in the laboratory. This, however, should not be too surprising as the pressures and temperatures prevalent in the Earth's mantle also are very different from what can be attained in a laboratory.

In view of the geographical connection of earthquakes with young mountain and island belts, it appears reasonable to assume that mountains and earthquakes alike are the expression of one and the same process, which has been called "orogenesis." There is, therefore, a strong indication that the

problem of mountain building also is directly connected with the mechanical behaviour of the Earth's mantle.

The ultimate elucidation of the process of orogenesis depends on the theoretical understanding of the mechanical behaviour of the material in the Earth's mantle under the there prevailing conditions; this has not yet been achieved.

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TRANSACTIONS OF THE ROYAL SOCIETY OF CANADA
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SECTION FOUR

Some Ordovician Halysitoid Corals

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Presented by J. F. CALEY, F.R.S.C.

ABSTRACT

The coral family Halysitidae is an unnatural group of species belonging to separate lineages, each of which happens to have assumed a chain-like habit of growth. Two species from the Simard beds of the Saguenay region, Quebec, and two from the Selkirk member of the Red River formation of southern Manitoba are described in detail. All but one of these species is new, and they are assigned to three genera. An unsuspected plasticity in growth is described in the Manitoba material.

ALL colonial corals must somehow reconcile the conflicting demands of efficient feeding and structural security. Maximum protection from buffeting by waves is afforded by a favositoid habit, each corallite being tightly appressed against its neighbours. Such a solid mass is very difficult to break up, but it is also very uneconomical. Each corallite, with its tentacles spread, is capable of gathering food from an area about twice the diameter of its own body, and this potentiality is sacrificed in a favositoid colony. Maximum food utilization is assured if the corallites are separated by a distance twice the length of a tentacle, but a group of such isolated cylinders is very fragile.

Each actual corallum is the result of the interplay of these needs and the potential adaptability of the species to its environment. Various corals respond in various ways. The distant corallites may be buttressed, as in *Syringopora*, or the space between them may be filled in with vesicular coenenchymal tissue, as in the heliolitids, and many other forms. The same species may vary its habit to accord with the environment, being massive in the surf and ramose in quiet water.

One of the ways in which corals have compromised between these demands is the halysitoid habit, in which corallites form thin ranks well separated one from the other, but strengthened by other ranks of opposite direction, the whole forming a rough meshwork when seen from above.

During the Middle and Upper Ordovician, at least five genetically distinct coral stocks adopted this peculiar habit. Bassler has described sixteen species of *Tetradium* which have done so (Bassler, 1950, pp. 284 et seq.), and Troedsson's *Columnaria halysitoides* (Troedsson, 1928, p. 113), which Bassler (1950, p. 274) considers a *Palaeophyllum*, has adopted the same growth form. All these species were recognized by the authors for what they are, and cause no taxonomic confusion. Three other Ordovician stocks, however, were described by authors more impressed by the chain than by

the animal making it, and these forms have been described as species of *Halysites*.

The recent redescription of the type species of this Gotlandian genus by Thomas and Smith (1954, p. 765 seq.) makes it possible to sort out some of the forms which have been included in it.

Descriptions of Genera and Species

QUEPORA, new genus

Type species, *Quepora quebecensis* (Lambe)

Lichenaria-like corals of halysitoid habit; thick-walled corallites with complete tabulae, no septa or other longitudinal structures, forming short moniliform ranks.

Quepora quebecensis (Lambe)

Plate I, Figs. 3, 5, 8, 12

Halysites catenularia var. *Quebecensis* (Var. nov.). Lambe, 1900, p. 69, pl. IV, figs. 1, 1a, 1b.

Catenipora quebecensis (Lambe). Buehler, 1955, pp. 46–7, pl. 7, figs. 1-3.

Typical Horizon: Middle Ordovician (probably Simard beds).

Typical Locality: Two miles south of Pointe Bleue, Lake St. John, Quebec.

Lectotype (Buehler, 1955): GSC 11305, W. McOuet and Jno. Leitch, collectors. Specimens here described, GSC 12384, 12385, Simard limestone, north of Ste. Anne de Chicoutimi, Quebec. (See Sinclair, 1953, p. 844, for details of this occurrence.)

This species has been adequately described by Buehler, and only a few notes are needed here. The lectotype is very coarsely silicified, and shows no details of structure. Lambe described his variety as having narrow tubules between the corallites, but I think that Buehler was correct in rejecting this interpretation. It will be noted that Lambe found the same spacing of tabulae in his tubules as in his corallites, a condition which would be very anomalous, since in most species with tubules they are much more closely tabulate than are the corallites. I have seen several specimens in which a rank has been broken away, leaving a narrow portion of the last corallite adhering, and giving an appearance very similar to that shown by Lambe.

A small specimen, 40 mm. in diameter, is figured to show the growth of the corallum on some tubular organic structure and, also, the clear separation between the corallum (including the matrix filling the lacunae) and the matrix. This corallum was apparently washed out of its original position after at least partial consolidation of the mud, and included as a pebble in its present site.

Since this species is the only one of the genus known with certainty so far, no comparisons are possible.

Quepora ? lacustris, new species

Plate I, Fig. 9

TYPE HORIZON: Middle Ordovician (Simard beds ?).

TYPE LOCALITY: Pointe Bleue, Lake St. John, Quebec.

HOLOTYPE: GSC 12386, J. Richardson, collector, 1857.

Corallum small, about 20 mm. in diameter, hemispherical (or perhaps, since it is broken at one end, cylindrical with a hemispherical distal portion), compact. Made up of very thick-walled, aseptate corrallites, arranged in short ranks with a maximum of four corallites to the rank, and thus surrounding small irregular lacunae, which are often no larger than the corallites around them. Tabulae not well exposed, but apparently thin, complete, and rather distant. Corallites elliptical in section, about 1 mm. long, ½ mm. wide.

This is an unsatisfactory species. The unique specimen affords less information than might be wished, but *Quepora* seems the best place for it. It is not a young *Q. quebecensis*, for we have many specimens of that species showing the growth of the corallum from its origin, and its corallites attain their full size very quickly and never show the minute crowded appearance seen here.

MANIPORA, new genus

Type species, *Manipora amicarum*, new species

A *Saffordophyllum*-like coral of halysitoid habit, the subquadrate corallites forming single or multiple ranks, tabulae complete, the inner walls of the corallites sporadically wrinkled to form discontinous longitudinal "septa."

Manipora amicarum, new species

Plate I, Figs. 1, 4, 10

Halysites catenularia var. *gracilis*, Hall. Lambe, 1900, p. 69 e.p., pl. III, figs. 6–7 (*non cet.*)

Halysites gracilis (Hall). Leith, 1944, pp. 268 seq., e.p., pl. 42, pl. 43, figs. 2–4 (*non cet.*)

Catenipora gracilis (Hall). Buehler, 1955, pp. 36 e.p. (not figured specimen).

TYPE HORIZON: Ordovician, Selkirk member of Red River formation. The position of the Red River is disputed, some holding it to be Upper, others Middle, Ordovician. I prefer the latter assignment, but the evidence is not conclusive.

TYPE LOCALITY: Tyndall (Garson), Manitoba. (GSC locality number 6837.)

HOLOTYPE: GSC 12382. Alice E. Wilson and Madeleine A. Fritz, collectors.

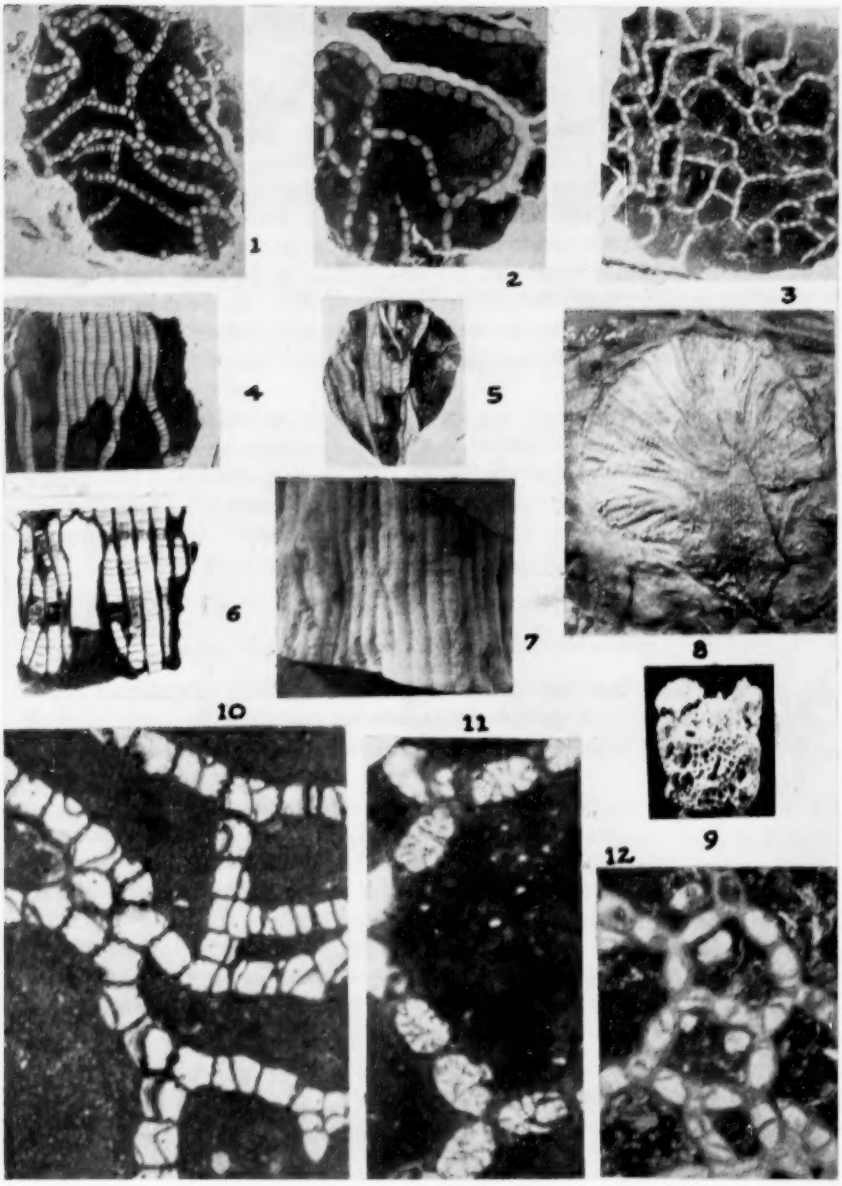

PLATE I (Figures approximately natural size except where noted)

FIGURES 1, 4 and 10—*Manipora amicarum* Sinclair. Transverse and longitudinal sections, and part of the former X 4, showing the spiniform "septa." Holotype, GSC 12382.

The holotype, now sliced, was a fragment about 90 mm thick, which gave no indication of the original dimensions of the corallum. Leith (1944) has recorded specimens showing a length of at least 558 mm., a height of 279 mm.

Growth very irregular, so that it is not possible to speak of a typical shape for the lacunae. Ranks usually single, but double ranks are common and favositoid patches are not rare. Corallites strikingly quadratic, with a slight tendency for the outer walls to be convex, but never to such an extent as to produce a moniliform appearance. Three to four corallites in a length of 5 mm., measured along to rank. Walls between corallites often quite oblique. (These features are well shown in Leith's illustrations.)

Tabulae thin, transverse, complete, equidistant, about nine in a length of 5 mm. No septa. The inner walls (i.e., the common wall if the rank is single, otherwise any wall other than that bordering the lacunae) frequently wrinkled. These wrinkles show in transverse sections as short, rather blunt spines. They were not seen in longitudinal sections, but broken specimens show that they are low ridges, two or three usually occupying the width of the corallite. They are not continuous throughout the length of the corallite (and thus are not seen in all corallites in a transverse section), but their maximum length cannot be stated. Certainly, they can continue for a few tens of millimetres.

Holotheca strongly, but finely, marked by horizontal lirae, presumably growth varices, about 20 per mm. These varices are occasionally crowded, or more prominent, but no direct relationship could be seen between this irregularity and the position of the tabulae. However, only in a very few places could this relationship be seen at all, and this negative observation should not be given much weight.

CATENIPORA Lamarck, emended

Type species, *Catenipora escharoides* Lamarck, *sensu* Thomas and Smith (see Thomas and Smith, 1954, p. 768 seq.)

Catenipora rubra Sinclair and Bolton

Plate I, Figs. 2, 6, 7, 11

Halysites catenularia var. *gracilis*, Hall. Lambe 1900, pp. 69–70, e.p., pl. III, fig. 5 (*non cet.*)

FIGURES 2, 6, 7 and 11—*Catenipora rubra* Sinclair and Bolton: no. 2, transverse section; 11, part of the same, X 4; no. 6, longitudinal section, showing two zones of abundant septa; no. 7, lateral view of a rank of corallites, the holotheca removed from the lower portion to show the faint longitudinal ridges. Hypotype, GSC 12383.

FIGURES 3, 5, 8, 12—*Quepora quebecensis* (Lambe): no. 3, transverse section; no. 12, part of the same X 4; no. 5, longitudinal section. Hypotype, GSC 12384. No. 8, natural section of corallum in matrix, showing tubular base on which it grew and dark line marking it off from matrix. Hypotype, GSC 12385.

FIGURE 9.—*Quepora lacustris* Sinclair. Holotype corallum, GSC 12386.

Halysites gracilis (Hall). Leith 1944, pp. 268 seq., pl. 43, fig. 5–6 (*non cet.*)

Catenipora gracilis (Hall). Buehler 1955, p. 36 e.p., pl. 4, fig. 7; pl. 5, fig. 1.

Catenipora rubra, new species. Sinclair and Bolton, Jour. Paleont., in press.

TYPE HORIZON: Ordovician, Selkirk member of Red River formation.

TYPE LOCALITY: Garson, Manitoba.

HOLOTYPE: University of Manitoba, no. 109.

Material here described: GSC 12383, topotypical, Alice E. Wilson and Madeleine A. Fritz, collectors.

This species has been adequately described, under the name *Halysites gracilis*, and only a few notes are needed here. As Leith has shown (1944, pl. 43, fig. 5) the spiniform septa originate at the thecal wall, and can be clearly traced through a thick sclerenchymous layer. Longitudinal sections show that the septa are sporadic in their occurrence, being present in zones about 2 mm. deep and separated by about 5 mm. of corallite in which septa are rare or absent. There are about four circles of septa between each pair of tabulae in the zones of their abundance. No lamellae have been seen, and for at least most of their length the septa are free circular spines, usually tapering, but sometimes slightly swollen distally. However, when the holotheca is removed, the outer surface of the theca shows faintly a series of low longitudinal ridges. These ridges cannot be counted with certainty, but they seem to average about five on the side of one corallite, and thus suggest a connection with the septa. The zonal occurrence of the septa, mentioned above, accounts for the fact that some transverse sections show an abundance of septa while in others they are few. The holotheca has very fine growth varices, about 30 in a length of 1 mm., thrown rather regularly into low undulations about ½ mm. apart.

NOMENCLATURE

Granted that different genetic stocks can be recognized in the corals hitherto referred to *Halysites*, how can their relationships best be expressed? I have suggested above that three genera should be recognized, because the species in them are unrelated, and only agree in a coincidence of growth form. But this course has been adopted with misgivings, and it might be well to at least point out the problem. It might have been better to describe *Manipora amicarum* as a new species of *Saffordophyllum*, and to refer *Quepora quebecensis* to *Lichenaria*. This has been our practice with the halysitoid *Tetradium* and *Palaeophyllum*, and I would have followed it here had these species not already been in the literature under the name *Halysites*. Placing them in separate genera seems to emphasize the un-*Halysites* nature of the species. This course will, I think, seem less radical when other species of these genera, which are known to exist, are described. Their description here would take this study too far afield.

Growth of Corallum

My picture of the growth of a halysitoid corallum was a very simple one, and, as far as I can find in the literature, it has been shared by all: a new corallite buds off the parent (or parents), a new rank is formed by the

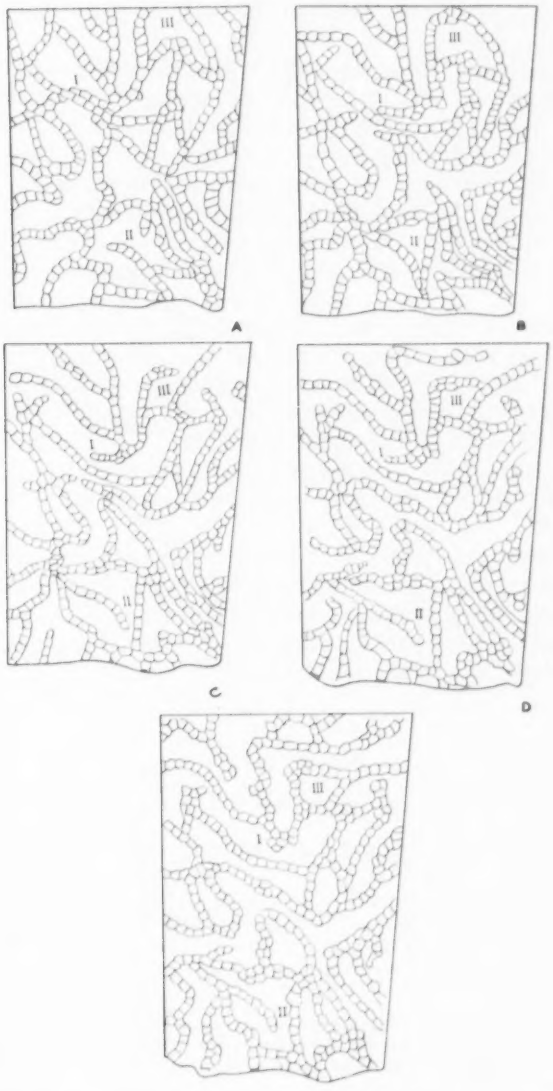

Figure 1.—Five surfaces of *Manipora amicarum*, about 3 to 4 mm. apart. *A* is lowest in the corallum, *E* the highest. Roman numerals I, II and III mark the same region on each surface. The upper edge of *A* is 42 mm. wide.

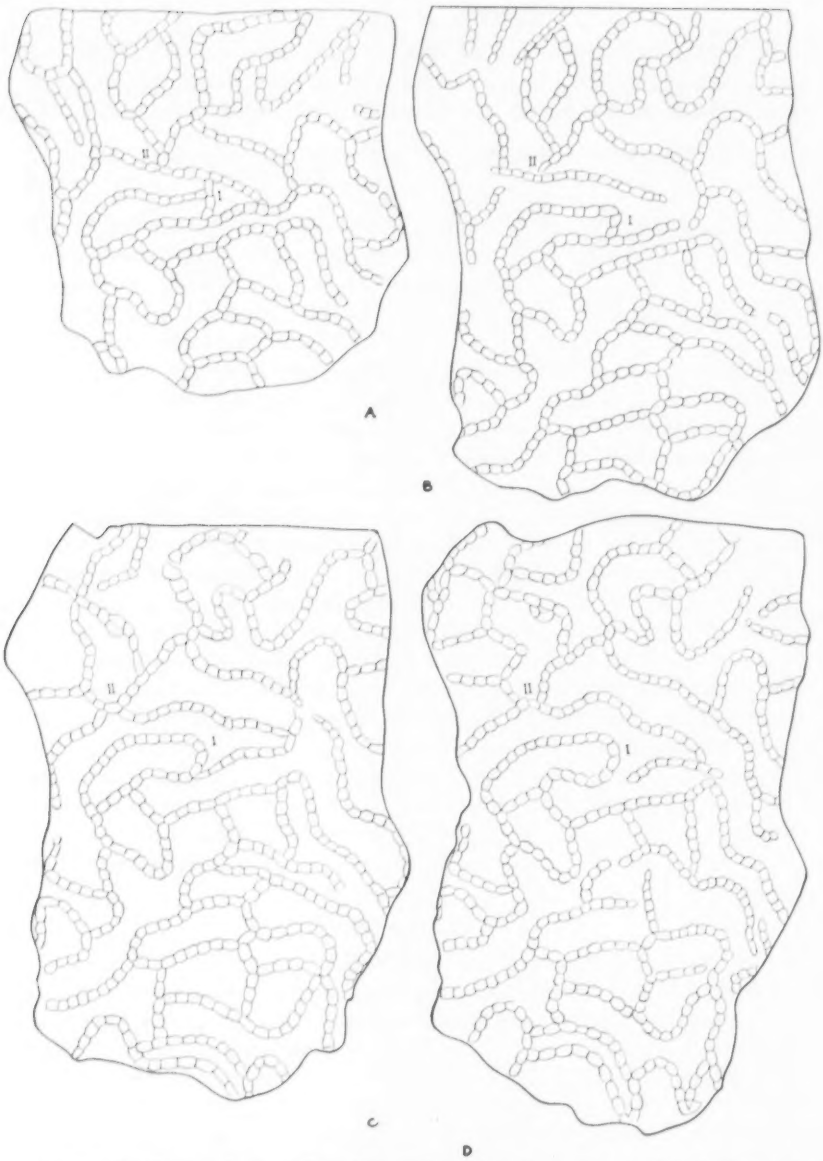

FIGURE 2.—Four surfaces of *Catenipora rubra*, about 4 mm. apart. *A* is the lowest in the corallum, *D* the highest. Roman numerals I and II mark the same region on each surface. The upper edge of *A* is about 62 mm. wide.

bridging of a lacuna, and then growth is regular and upward, the corallum growing regularly by the introduction of new individuals from time to time. To my surprise, I found that this picture was not accurate.

As the corallum grows, ranks break up, form new connections, and in general behave in such a manner as to suggest that writhing is the proper word to describe the behaviour. This would not have surprised me, had I remembered that the corallum, as we have it, is only the dead record of the colony, and that always beyond the stony tubes was living tissue, which had movement, and individuals which could attach now to this, now to that, neighbour.

Figure 1 shows five surfaces of the holotype of *Manipora amicarum*, about three or four millimetres apart. *A* is the lowest, *E* the highest in the corallum. At I we have three secondary limbs breaking away from the main transverse rank, the two lower ones (in the figure) then uniting to form a new rank, the upper one withering away. At II a rank which had been free at its upper end grows upward to meet another rank, and then looses its lower connection. At III a loop opens, a new rank appears between the segments, one of which then unites with it. Other such evidences of an extreme plasticity can be seen in the figure.

The same type of growth is seen in *Catenipora rubra*. Four surfaces, again about 4 mm. apart, are shown in Figure 2. I have marked only two of the more striking changes in position of the ranks. That marked I involves the same kind of dissolution of connections which were seen in the other species, and can be followed better in the figure than by verbal description. At II we have a rank (descending) joined to another, becoming free, and then reuniting with the same rank, but now four corallites further to the left.

To what extent this growth pattern is found in other halysitoid corals I do not know. Specimens of *Tetradium* suitable for such sectioning will be sought, and it may be that this is the way in which all halysitoids grow.

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SECTION FOUR

Uranium-Rich Thorianite from Pontiac County, Quebec

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ABSTRACT

Thorianite, a radioactive mineral not previously recorded from Quebec, has been found in Grenville limestone in Huddersfield Township, Pontiac County. It occurs as black grains 0.1 mm. to 0.2 mm. in diameter widely scattered in a matrix of coarse crystalline limestone. The mineral was first concentrated, and then identified by its crystal form, X-ray fluorescence spectrum, and X-ray diffraction pattern. The thorianite is itself uranium-rich, and is not associated with uraninite. A uranium-bearing hydrous thorite has also been identified, associated with diopside and calcite in adjacent lime-silicate rock.

THE mineral deposits of the Yates Uranium Mines Inc., in southwestern Quebec, are of interest because they include uranium-rich thorianite, a radioactive mineral not previously recorded from Quebec, and also because this mineral is interspersed in streaks and lenses in the rock and is not associated with veins or dykes. The Yates property is located in the central part of Huddersfield Township, Pontiac County (Figure 1).

The principal rock is a contact phase of Grenville (Precambrian) limestone (Logan, 1863; Dresser and Denis, 1944) extensively metamorphosed by the adjacent igneous rocks. The limestone is a greyish-white medium-grained crystalline rock with streaks and lenses of very coarse-grained salmon-pink calcite; dolomite is not present. Pale green diopside is an important constituent and in places is sufficiently abundant to give the rock a green colour. Flakes of amber-brown phlogopite mica occur abundantly, especially with the salmon-pink calcite. Muscovite mica, chondrodite, tremolite, fluorite, and graphite are minor constituents.

The original find of radioactive material was in a pit from which phlogopite and fluorite had been mined many years before. Here uranium-bearing thorite (uranothorite) was found in a pegmatite dyke-rock characteristic of the mica mines in the Grenville (Wilson, 1924). The thorite is associated with fluorite, calcite, phlogopite, apatite, and diopside. As Lindgren (1933) has pointed out, these Grenville pegmatites are in part certainly derived from limestone by contact metamorphism; they do not have the mineral composition of the usual pegmatite dyke.

The uranothorite occurs as brown patches of irregular shape and size and as small tetragonal prisms. It is seen between and within crystals of salmon-pink calcite, diopside, and fluorite. In places cracks radiate out from the thorite grain into the enclosing crystal showing the shattering effect of radioactive disintegration and the hydration of the thorite. The thorite is metamict and is largely altered to a resinous, honey-coloured material. This

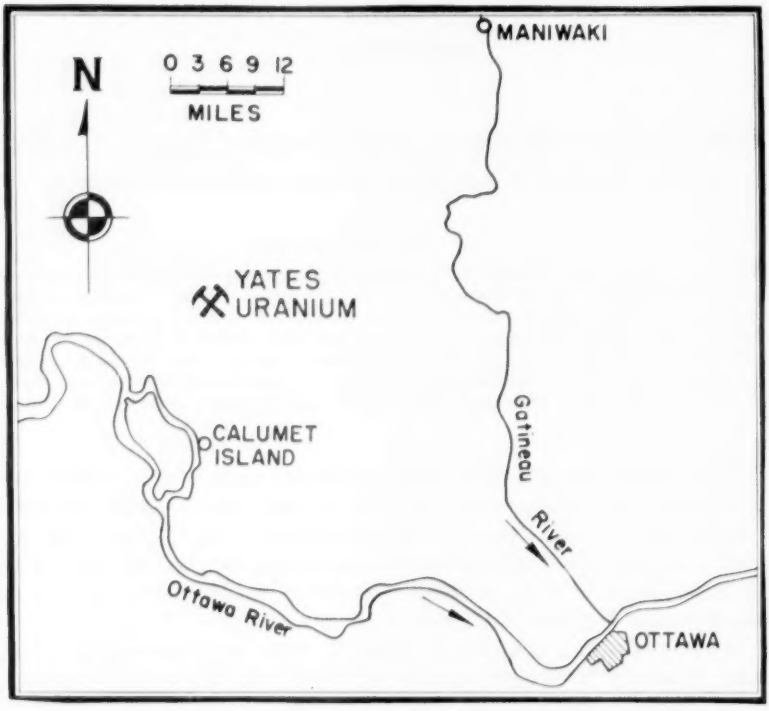

FIGURE 1.—Map showing location of Yates Uranium property.

alteration product is isotropic with a refractive index of 1.606; it appears to be the hydrous basic sulphosilicate to which Ellsworth (1927) gave the name, Beta-hyblite. Although George (1949, p. 95) has questioned the value of a special name for such material, the term serves a useful purpose in designating the mineral found here. Analyses by X-ray fluorescence have shown that both uranium and thorium are abundant in the specimens, and that columbium (niobium), tantalum, and rare earths are not present. In specimens where the radioactive content was lower than usual, the thorite was seen to be pseudomorphically replaced by calcite.

The Yates uranothorite occurrence seems to be similar to those in the Bancroft area, Ontario (Satterly and Hewitt, 1955).

Further prospecting of the Yates property led to other finds of radioactive mineralization in areas where no pegmatite occurs. The radioactivity is largely associated with the bands and lenses of coarsely crystalline salmon-pink calcite and phlogopite, and it was this portion of the metamorphosed limestone that was given intensive study. The first suite of thin-sections did not reveal the radioactive mineral, but a careful search of the material with a stereoscopic microscope showed the presence of widely scattered grains

of a lustrous black mineral. The very small size of the grains and their occurrence as widely scattered individual grains necessitated making a concentration of the grains.

A large-sized hand specimen was crushed in a laboratory jaw-crusher set to the finest crushing size, about ¼ inch, and by repeatedly crushing and screening, a large proportion of the rock was crushed to considerably less than ¼ inch. Further crushing by pulverizing was not done, because of the extreme brittleness and tendency to sliming of most radioactive minerals. Excessive sliming would reduce considerably the amount of concentrate that would be satisfactory for further study.

The crushed material was then digested for a period of about four hours with 10 per cent hydrochloric acid, by repeatedly treating with acid, washing away the "spent" acid, and renewing the acid. This process of concentration dissolved out the calcite but was not so severe that any other minerals were attacked by the acid. By study of the insoluble residue so obtained under the binocular microscope, it was seen that the crushing and acid treatment had been sufficient to "unlock" the several minerals in the rock and that no further crushing was needed.

The insoluble residue from the acid leach was then panned in an ordinary gold pan. In this way it was possible to wash off nearly all the mica, which was quite abundant, as well as the lighter silicate minerals The pan-concentrate contained an appreciable amount of the black mineral, but not enough for positive identification.

Panning supplied a concentrate that was sufficiently small in volume for further gravity separation using heavy liquids and sink-float technique. In this process the pan-concentrate was repeatedly concentrated using methylene iodide (specific gravity 3.3) in a small separation funnel, and a separation made of material with a specific gravity above 3.3 from material with a specific gravity below 3.3. In this way a concentrate containing about 25 per cent of the black mineral sought was obtained.

This heavy fraction from the methylene iodide separation was studied under a binocular microscope. The black mineral was seen to occur both as fragments and as reasonably well shaped crystals. The crystal forms recognized included modified cubes, octahedra, and dodecahedra, with a few interpenetration twins. This information served to classify the mineral as isometric.

Grain size measurements were made on the black grains and about two-thirds of the material was found to be about 0.1 mm. or 150 mesh in diameter and the remaining one-third about 0.2 mm. or 65 mesh in diameter.

None of the material was magnetic.

A small amount of this heavy-liquid concentrate was crushed to a very fine powder and an X-ray fluorescence spectrum made. This spectrum showed that the heavy elements present included principally thorium and uranium, with thorium more abundant than the uranium; some lead,

probably radiogenic lead, was indicated. No columbium (niobium), tantalum, or rare earths were detected.

The crystallographic features and the fluorescence spectrum suggested that the black mineral would be thorianite, or, because of the abundant uranium, a mixture of grains of thorianite and grains of uraninite. Because of the very similar physical properties of these two minerals, it was decided to investigate the possibility of a mixture of the two minerals by making an X-ray diffraction study of the black grains. To do this it was necessary to obtain a clean sample of the black mineral without contamination from other minerals. This was done by picking out, under the binocular microscope, with a pointed tooth pick, individual grains of the mineral until enough grains were obtained for pulverizing and packing into a capillary tube for X-ray diffraction technique.

Using spectrometer technique a graph was obtained showing the X-ray diffraction pattern of the material. On this graph the principal peaks, corresponding to the principal "d" spacings of 3.22, 1.96, and 1.68 of thorianite, were identified. No peaks for uraninite were indicated, so the mineral was identified as the uranium-bearing thorianite, uranothorianite, and not a mixture of two minerals. Because of the diffraction pattern obtained, it may also be concluded that much of the thorianite is not metamict.

In order to obtain information concerning the relationship of the uranothorianite to the other minerals in the rock, further thin-sections were made and some sections were finally obtained which showed the black mineral. In Figure 2 a small cube of uranothorianite is seen in a diopside crystal, surrounded by a prominent reaction rim. Figure 3 shows the calcite-diopside rock with the thorianite in the calcite crystals as irregular patches. The

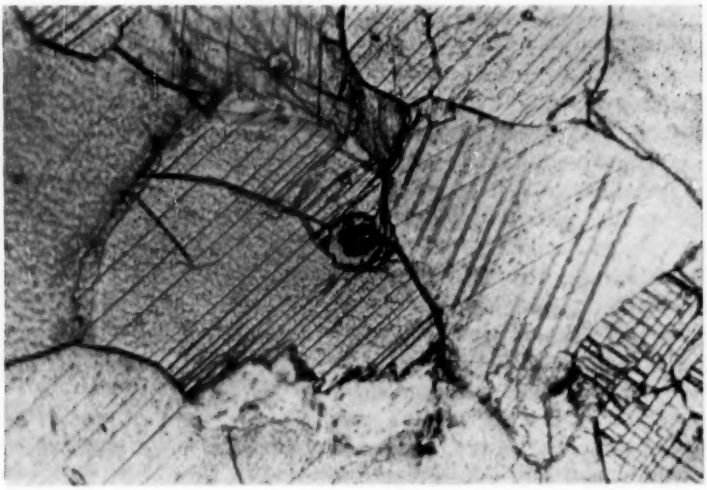

FIGURE 2.—Photomicrograph of small cube of uranothorianite in diopside. ×80.

FIGURE 3.—Photomicrograph of patches of uranothorianite in calcite. ×80.

radioactive disintegration of the surrounding mineral by the thorianite is also seen here.

The genesis of the radioactive minerals of the Yates property appears to be related to the general contact metamorphism of the limestone; these minerals seem to be among the early minerals formed at that time, rather than a later introduction into the rock from veins or dykes. However, the concentration of the uranothorianite in the bands and streaks of salmon-pink calcite suggests some structural control and not a complete dissemination throughout the rock.

Thorianite is classed as "very rare" by Page (1950). Because the small grains of thorianite are rarely visible except when concentrated by streams or other means, it is not surprising that it remains a rarely identified mineral despite its wide geographical distribution. It was found originally in Ceylon associated with other heavy minerals in stream gravels (Palache, Berman, and Frondel, 1944). Most other occurrences are of similar nature: in Madagascar in alluvial deposits, in the black sands of a gold placer on the Boshogoch River, Siberia, and in black sand concentrates from Sweepstakes

Creek, Alaska, the Missouri River near Helena, Montana, and the Scott River, California (George, 1949, p. 82).

At Easton, Pennsylvania, uranothorianite occurs in serpentine at the contact of limestone and pegmatite (Palache, Berman, and Frondel, 1944). In northern Saskatchewan, thorianite is reported from the Row group, on the south shore of Charlebois Lake, where the mineral occurs in a zone of sheared pegmatitic rock along a contact between granitic and sedimentary rocks, and is associated with much biotite and some molybdenite and uraninite (Lang, 1952).

The possibility is suggested that other areas of the Grenville where the salmon-pink calcite-phlogopite bands are present might be of interest for similar study.

The helpful co-operation of Mr. Phillias Matte, President, Yates Uranium Mines Inc., is gratefully acknowledged.

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TRANSACTIONS OF THE ROYAL SOCIETY OF CANADA
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SECTION FOUR

Biogeochemical Prospecting in Northern Latitudes

HARRY V. WARREN, F.R.S.C., and ROBERT E. DELAVAULT

ABSTRACT

In northern latitudes there are some areas where there may be permafrost and others where soils may not be present or are poorly developed. In such areas it is not practical to use soil sampling in any search for buried ore deposits. Preliminary work has indicated that biogeochemical methods can be successfully employed in northern latitudes. Birch (*Betula papyrifera* and *B. glandulosa*), Labrador Tea (*Ledum groenlandicum*), Spruce (*Picea mariana* and *P. glauca*), and Willow (*Salix* sp.) have all been collected in arctic or near-arctic conditions and found to be capable of reporting anomalously high zinc and copper contents in underlying rocks.

Introduction

IN 1953 Dr. C. S. Lord published *Geological Notes on Southern District of Keewatin, Northwest Territories* (Paper 53–22, Geol. Sur. of Can.). This paper clearly indicated the manner in which helicopters may assist prospecting in northern latitudes. Informal discussions led the authors to investigate the possibility of biogeochemistry also being able to aid geologists and prospectors in their work in northern latitudes.

Geochemical Problems in Northern Latitudes

Many geochemical techniques are impractical in northern latitudes. During long periods water testing is useless. For the greater part of the year there is no run off and when there is a run off it is usually of surface water. Oxidizing zones of ore bodies and the water in streams are only connected during a comparatively short period of the year. Soil sampling likewise presents special problems. Frozen ground and lack of residual soil suggest difficulties which, although they may not be insurmountable, do in many areas make soil sampling difficult and unreliable.

In many areas mineralization is associated with shearing and consequently is found in lower ground. Higher ground where glaciation has cleaned off soil and there are good rock exposures seldom exhibits mineralization or tell-tale oxidation. On lower ground and on ground where there is permafrost there may be some vegetal growth, either trees, lesser plants, or mosses and lichens.

This paper reports some preliminary results obtained from sampling in northern latitudes and analysing some relatively well-known species near and away from known mineralization.

Unless otherwise stated all the analyses which follow are from samples carefully selected from second-year stems and are expressed in parts per

million (p.p.m.) dry plant followed by the parts per million, between brackets, in ash. Samples taken near known mineralization are spoken of as positive and those near no known mineralization as normal or negative.

Labrador Tea (*Ledum groenlandicum*)

Experience in southern Ontario and Quebec lead us to suggest that there the normal copper and zinc contents of Labrador Tea are close to 7(300) and 64(2800) respectively. Three negative samples sent to us from Ungava ran 7(550) in copper and 27(2200) in zinc.

When sampling an unknown area which has different climatic and geological conditions it is always prudent to attempt to set up controls by selecting samples both from positive and negative ground. From permafrost areas in the Yukon and Northwest Territories we obtained the following results.

TABLE I

Area	No. of samples	Nature of Sample	Copper	Zinc
Northwest Territories	1	negative	10(430)	26(1100)
Northwest Territories	2	Cu weak, Zn medium	9(680)	62(4800)
Yukon Territories	5	negative	6(230)	100(4000)
Yukon Territories	5	Cu Tr. Zn strong	11(520)	260(12160)

Probably all that may be deduced from the above is that Labrador Tea most decidedly does report zinc in permafrost areas. If it be emphasized that, in the area sampled in the Yukon, copper was economically negligible then it may be assumed that Labrador Tea can, under reasonable conditions, also report the presence of copper.

Twenty-three other samples have been analysed and the results have confirmed the above conclusions.

Scrub Birch (*Betula glandulosa*)

In the mountainous areas of British Columbia, on the basis of eleven carefully selected samples, we suggest that for this species the copper and zinc normals may be 7(480) and 160(11,100) respectively. Four negative samples sent to us from Ungava averaged 6(500) and 175(14,000) in copper and zinc respectively.

Two samples sent to us from the Coppermine Area, Northwest Territories, provided the results shown in Table II, which may properly be described as striking.

From the Yukon we obtained no samples from any unmineralized area but samples close to known mineralization were higher than those taken some distance away. Seven samples from an area comparatively close to known zinc mineralization with which insignificant quantities of copper

TABLE II

Area	Nature of sample	Copper	Zinc
Coppermine	Cu positive Zn negative	232(18,000)	221(17,000)
Coppermine	Cu negative Zn negative	9(780)	210(18,000)

were associated averaged in copper 9(450) and in zinc 450(22,400). Samples taken from the vicinity of known zinc veins ran much higher in zinc. Limited though the above evidence may be, it does signify that dwarf birch, known in some areas as "buckbrush," can, to a marked degree, reflect the presence of copper or zinc mineralization.

Willow (*Salix sp.*)

Because there are many varieties whose identification is difficult, willow has on the whole proved unsatisfactory for biogeochemical purposes. In British Columbia copper and zinc normals were suggested at 7(270) and 80(3100) respectively and in southeastern Canada the corresponding figures were 8(250) and 240(8000). The fact that many British Columbian soils are notoriously deficient in zinc may account for the wide divergence in the zinc content of the eastern and western willow. Two negative samples from Ungava averaged in copper 7(380) and in zinc 160(9300).

The only willow growing on known mineralization in a permafrost area so far made available to us comes from the Coppermine Area of the Northwest Territories. In the area from which our samples were collected, copper mineralization is widespread, but pyrite is conspicuous by its absence and no zinc minerals have yet been reported. Five positive samples assayed 20(820) and 220(9100) in copper and zinc respectively. A negative control from nearby ran 9(340) and 85(3000). The copper results were highly gratifying but an explanation for the zinc remains as yet undiscovered.

"Reindeer Moss"

Three samples of "reindeer moss," two copper positive and one negative, were collected for us for analysis and study. This "Reindeer moss" turned out to be a complex mixture of lichens, and several vascular plants. Two expert botanists, Dr. Krajina and Dr. Szczawinski of the Department of Biology and Botany of the University of British Columbia, kindly sorted the samples into their various components. In each sample four or five species were found to be predominant but only three lichens were present in all samples: these were *Cornicularia aculeata*, *Alectoria ochreleuca*, and *Citraria cucullata* and of these only the first named was present in sufficient amounts for chemical analyses. Some of the other constituents were investigated spectroscopically and they showed marked variations in their copper content. Furthermore these variations coincided with the presence or absence of mineralization.

One vascular plant, *Silene acaulis*, was present in one positive sample in sufficient amounts for chemical analysis. Table III shows the striking results obtained from the analyses of some of the components of "reindeer moss."

TABLE III

Species	Character	Copper	Zinc
Cornicularia aculeata	+	160(16,000)	61(6200)
Cornicularia aculeata	+	180(35,000)	27(5000)
Cornicularia aculeata	−	4(300)	26(2100)
Silene acaulis	+	135(1600)	97(1100)

Because of a lack of positive zinc samples we are unable safely to deduce anything about the response of "Reindeer Moss" to zinc. However the response to copper exhibited by the above samples may be termed spectacular.

Black Spruce (*Picea mariana*); White Spruce (*Picea glauca*)

We were fortunate enough to obtain enough samples of each of these species to justify the presentation of results by means of histograms. Two samples of black spruce came from Ungava, all the remainder from a zinc positive area in the Yukon where copper is known, but only in quantitatively modest amounts.

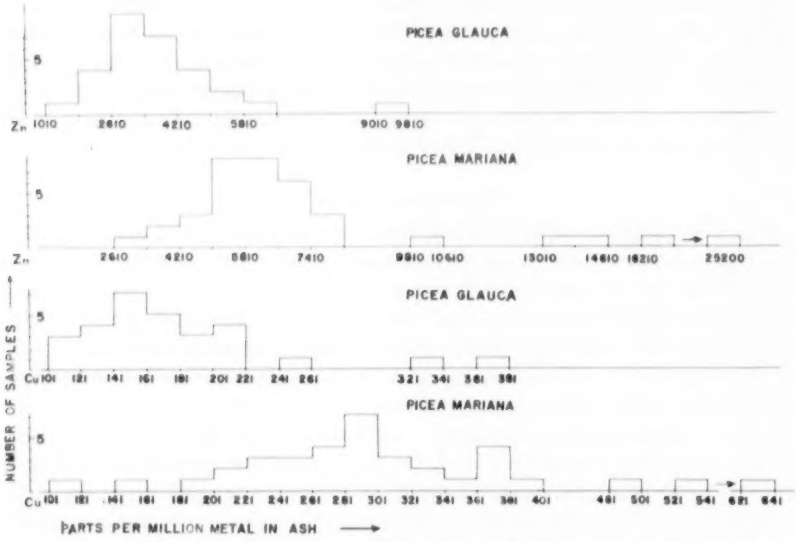

Figure 1.—Zinc and copper content of *Picea glauca* and *Picea mariana* growing on permafrost. (In p.p.m. of metal in ash of twig.)

The four histograms which appear in Figure 1 speak for themselves. All are asymmetric with more specimens on the high content side of the diagram than would be normal in a negative area. The highest frequencies correspond to greater contents of zinc than are normally found in more southerly latitudes. For *Picea mariana*, around 6000 p.p.m. in ash is well above the 3200 p.p.m. which we have found to be the average for many hundreds of samples taken in southeastern Canada. These results may in part be caused by climatic effects and in part by some diffusion of mineralization.

At all events there are enough high samples outside the main body of the histograms to indicate that these species can and do respond to mineralization in permafrost areas.

Conclusions

On the basis of preliminary studies it seems obvious that biogeochemistry holds promise of providing another useful tool which will assist geologists and prospectors in exploring the northern latitudes of Canada. However much more experimental work will have to be done before it will be possible to set up valid "normals" for the various pertinent species.

In the opinion of the authors further work on biogeochemistry in northern latitudes is fully justified.

Acknowledgments

The Geological Survey of Canada have contributed a substantial portion of the funds which made this research possible. Kennco Explorations (Canada) Limited, Dr. J. Rousseau (Director of the Montreal Botanical Gardens), and United Keno Hill Mines Limited all assisted greatly by collecting suites of specimens and by giving permission to publish some of the results which appear in this paper. Miss C. Cross made many of the analyses and our colleagues Dr. Krajina and Dr. Szczawinski spent considerable time working on the "Reindeer Moss."

To all the above individuals and organizations and to the many others who assisted us the authors wish to express their gratitude.

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SECTION FOUR

The Age of the Fossil Hill Coral Reefs

M. Y. WILLIAMS, F.R.S.C.

ABSTRACT

Alexander Murray (1847–8) and Robert Bell (1866) included the Fossil Hill beds in their "Niagara Formation." In 1912 and subsequently M. Y. Williams included the Fossil Hill beds in his undivided Lockport formation, correlated with the Lockport formation of New York State. In 1938–9, E. R. Cumings concluded, mainly on stratigraphic evidence, that "The massive Lockport dolomite of Ontario traces westward into the Engadine of Michigan, which is believed to be Racine. The Racine is therefore Lockport, and the Manistique and Burnt Bluff formations are below the Lockport and are possibly Clinton." Cumings places the Fossil Hill beds in the Manistique formation and he and G. M. Ehlers (1942) chart the Manistique of Ontario as equivalent to the upper Rochester and an hiatus below the Lockport in New York State. T. E. Bolton (1953) proposes a general revision of the section on Georgian Bay which would separate the coral horizon into the "Fossil Hill formation," of which he says, "Exposures of argillaceous, dense Fossil Hill dolomites observed south of Orangeville could be traced south into lithologically similar dolomites that were definitely correlative with the Clinton Reynales formation." In this paper, the author questions the validity of stratigraphic correlations along 300 miles of discontinuous outcrops, interrupted by water gaps up to 24 miles across and totalling over 75 miles. He reviews the fossil evidence and concludes that the Fossil Hill beds do not occur as an extensive mappable unit, but belong in the Lower Lockport formation, of about the time equivalent of the Gasport beds of Niagara River.

The Problem

THE Fossil Hill coral beds, extensively exposed about seven miles southwest of Manitowaning, Manitoulin Island, Ontario, are typical of middle Silurian coral assemblages occurring westward across Canada. Whether as reefs (bioherms) or sea-floor carpets (biostromes) characteristic Niagara coral beds have been recorded from Lake Timiskaming, the Attawapiskat River, central Manitoba, at various localities in the Rocky Mountains, in the Franklin Mountains, in the Arctic Archipelago, and elsewhere.

In the United States, Niagaran reefs are widely distributed south and west of the Great Lakes (Lowenstam, 1950). Similar biotic assemblages and structures occur in Gotland and in England.

Because of its accessibility, richness in numbers and species of corals, stromatoporoids, and associated forms, the Fossill Hill fauna has become a convenient reference for dating similar Silurian occurrences across Canada. Such a reference is very important, as corals maintain recognizable characters long after most fossils are all but obliterated by weathering or silicification. It is safe to say that most of the Silurian formations of western and northern Canada would be but doubtfully dated were it not for their "Haly-

sites" and "Favosites" beds. As a rule, lower and higher Silurian formations are dated by reference to the coral-bearing formations. This being the case, the age of the Fossil Hill coral horizon is of great importance.

Former Age Conclusions

Alexander Murray (1847–8) and Robert Bell (1866) mapped the dolomite around Fossil Hill in their "Niagara Formation." Travelling mostly by sail-boat, they apparently missed Fossil Hill itself, which is inland, but Bell described the Fossil Hill horizon which occurs from 80 to 120 feet above the base of the section on High Hill east of West Bay. From Bell's collections, Billings identified 13 species of corals, one stromatoporoid, one cephalopod, and *Pentamerus oblongus*.

In 1912 the writer commenced his studies of the Silurian of Ontario on Manitoulin Island and for five years gave his undivided attention to mapping and correlating the formations concerned. He measured twenty-three sections between Niagara Falls and Cabot Head and examined the outcrops throughout the eighty-mile length of Manitoulin Island and on Cockburn Island. He visited Fossil Hill on numerous occasions in 1912, 1915, 1920, and 1935. In 1912 he was associated for a time with Charles Schuchert, A. F. Foerste, W. A. Parks, and T. L. Walker.

Fossil Hill Section

	Top of Hill	Feet
"Lockport" dolomite	Massive unfossiliferous dolomite	30
	Branching bryozoa beds	25
	Pentamerus beds	5
	Medium bedded, many cup and other corals	20
	Medium bedded unfossiliferous	30
	Thick bedded dolomite with corals	25
	Fossil Hill beds and reefs	8
	Stromatopora and corals in thick-bedded dolomite	18
	Medium-bedded dolomite	35
	Thin-bedded dolomite	35
Cataract	Wingfield shale	20
	Dyer Bay dolomite	25
	Cabot Head shale, red and green	57
	Manitoulin dolomite	60
Ordovician	Richmond shale	

The above section is the result of the writer's various studies; thicknesses are hand-levelled.

The upper massive unfossiliferous dolomite is similar to the dolomite below the Eramosa beds on Fitzwilliam Island 15 miles to the southeast and it is most probable that not more than 20 to 30 feet of dolomite and about 25 feet of thin Eramosa beds are lacking at Fossil Hill to complete the "Lockport section," which would be about 275 feet thick. If some of the thin beds at the base prove to be St. Edmund dolomite, the "Lockport" will be reduced in proportion to their thickness.

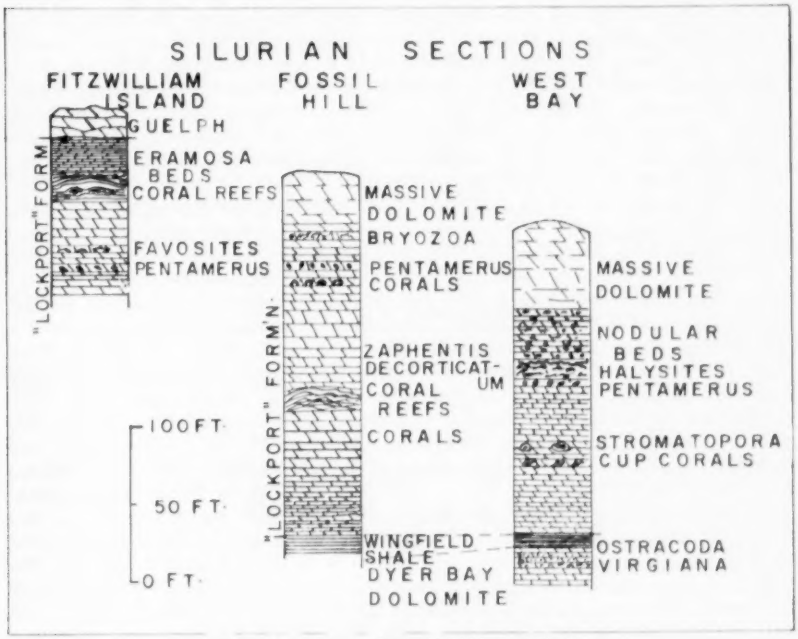

FIGURE 1.—Age of Fossil Hill coral beds.

In 1938, E. R. Cumings wrote in his abstract (in part) as follows:

The Cordell coral beds of the Manistique come in in the Bruce Peninsula at Lion Head and continue through Manitoulin (Fossil Hill beds) into Michigan, and have at their base the *Pentamerus* bed from Owen Sound northward. . . . The massive Lockport dolomite of Ontario traces westward into the Engadine of Michigan, which is believed to be Racine. The Racine is therefore Lockport, and the Manistique and Burnt Bluff formations are below the Lockport and are possibly Clinton.

This conclusion differs from that of Ehlers (1919) who makes only the upper part of the Lockport equivalent to the lower part of the Racine, the "Upper Coral Beds" belonging to a lower division of the Lockport. Ehlers placed the upper part of the Racine in the Guelph following the Michigan Geological Survey (also James Hall, A. C. Lane, 1908, and R. A. Smith,

1915). This appears to be the first suggestion that the Fossil Hill beds might be "Clinton." Whatever the Burnt Bluff may be, there is still room in the lower Lockport and upper Rochester for the Manistique formation.

Cumings (1939) defines the Lockport as having three members—Gasport dolomite, Suspension Bridge dolomite (new name), and Eramosa dolomite. He describes the changing facies at Dundas and says:

> Ten miles north of Hamilton . . . the character of the Lockport has completely changed again, and the entire formation consists of very massive light gray, coarsely saccharoidal dolomite, the lower portion of which apparently corresponds to the Gasport. This lithologic facies persists to the north through Bruce peninsula and on into Manitoulin Island and Upper Michigan, where it is called the Engadine dolomite. It is correlated with the Racine of Wisconsin. Racine fossils have been collected in the Engadine near Wiarton. It is overlain in Ontario by the Eramosa dolomite. At Cataract, Ontario, the Engadine rests on the Cataract (Medina) shales, the entire Clinton group being absent. To the northwest, in Bruce peninsula and Manitoulin Island, the Manistique and Burnt Bluff formations make their appearance, and reach their maximum development in northern Michigan. Cataract therefore, lies on an axis or barrier which in Clinton time separated the New York–Southern Ontario sea from that of the Michigan basin. This is here called the Cataract axis. From Owen Sound northward the base of the dolomite sequence, above the Medinan, is a massive bed filled with a large species of *Pentamerus* (Pentamerus Bed). This has been traced into Michigan where it becomes a double bed at the base of the Manistique formation. From Lion Head northward a thin-bedded dolomite rich in corals (35 feet at Lion Head, 65 feet at Dyer Bay) lies between the Pentamerus bed and the Engadine dolomite; this runs westward into the Cordell (Manistique) coral beds of Michigan and Wisconsin, superabounding in corals of the genera *Arachnophyllum*, *Syringopora*, *Thecia*, *Favosites*, *Alveolites*, *Cladopora*, *Coenites*, *Halysites*, *Heliolites*, *Plasmopora*, *Lyellia* etc. This is the horizon of the famous Fossil Hill coral bed on Manitoulin Island. At Dyer Bay a 7½ foot stratum of dense brown finely jointed dolomite lies beneath the *Pentamerus* bed, and disconformably on the Wingfield shale of the Cataract (Medinan). This is the St. Edmund dolomite of Williams, which he mistook for a local lens. It contains *Camarotoechia Winiskensis* and expands on Manitoulin Island into a portion of the Burnt Bluff formation of Michigan. The thickness of the Burnt Bluff on Manitoulin is 170 feet, and it probably represents both Byron and Hendricks beds.
>
> The correlation of the Burnt Bluff and Manistique formations is a matter of considerable difficulty. Heretofore they have been placed in the Lockport group. They are, however, definitely below the Engadine (Lockport). They cannot therefore, be Lockport. Since they were deposited in a separate basin from the New York Clinton, and have quite a different fauna, they cannot be exactly correlated with the Clinton. The presence of the genus *Huronia* in the Manistique of Michigan has, nevertheless led Foerste to correlate the latter tentatively with the Clinton; and it may be that both the Burnt Bluff and Manistique were laid down in Clinton time; or they may occupy a hiatus between the Rochester and Lockport.

The writer is not in accord with Cumings' description of the St. Edmund dolomite and Burnt Bluff occurrences on Manitoulin Island. In the excellent section at West Bay, the Dyer Bay dolomite is 25 feet thick and carries *Virgiana mayvillensis* and characteristic ostracoda. The Wingfield shale is about 8 feet thick and is overlain by 20 feet of thin-bedded dolomite

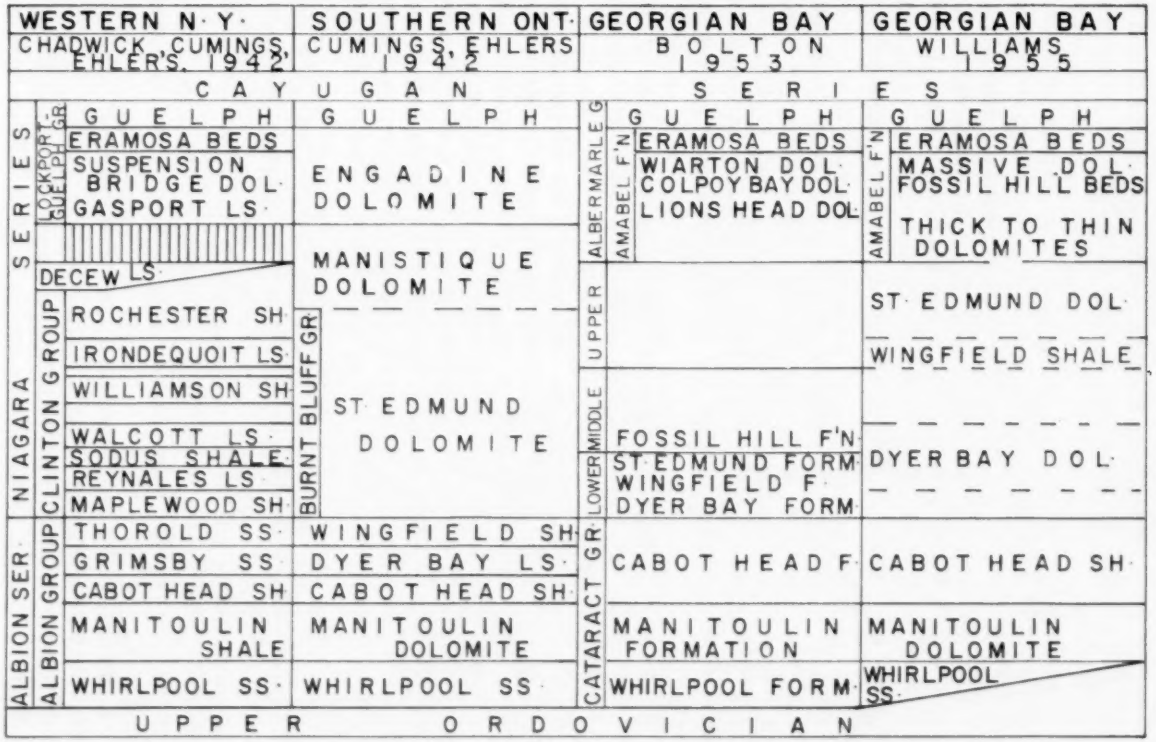

FIGURE 2.—Classifications of Lower and Middle Silurian formations.

below a talus-covered interval. The Fossil Hill horizon occurs about 120 feet above the top of the Dyer Bay dolomite, and has a *Pentamerus* zone at its base. This is unlike the occurrence at Fossil Hill where the *Pentamerus* zone is higher up.

The only beds here which could be St. Edmund are the 20 feet of thin beds above the Wingfield shale, including possibly some of the beds covered by talus. These, however, are similar to thin-bedded dolomites occurring at Cabot Head where a few feet of shale intervenes between them and the St. Edmund dolomite below. There is no room here for 170 feet of Burnt Bluff beds between the Dyer Bay dolomite and the *Pentamerus* zone above, even if the whole lower section is called St. Edmund. The writer measured this interval as 120 feet.

Cumings gives no details regarding the sections of St. Edmund dolomite on Manitoulin Island and he does not mention the characteristic fossils found in it at the type locality, viz., *Favosites cristatus* and *Atrypa parksi*, but says "It contains *Camarotoechia winiskensis*." The only occurrence of *Camarotoechia winiskensis* found by the writer was in Guelph dolomite at Tobermory.

That beds of St. Edmund age occur on Manitoulin Island is possible but they are probably thin as at their type locality and poorly differentiated from the beds above them.

Cumings and Ehlers (Swartz *et al.*, 1942) divided the Niagara of Ontario below the Guelph into the Engadine dolomite and the Manistique dolomite. These names do not occur on any map of Ontario nor on any of the adjoining maps of New York which include the type Silurian sections. The names are carried over from Michigan along a line of discontinuous outcrops 300 miles in length. A 50-mile water-gap separates the western end of Manitoulin Island from the Northern Peninsula of Michigan, and water-gaps, one 25 miles wide, separate Manitoulin Island from the mainland of Ontario.

In their correlation chart Cumings and Ehlers show the Engadine as the equivalent of the Lockport dolomite, the Manistique representing the upper part of the Rochester shale, the DeCew limestone and the hiatus between the DeCew limestone and the Gasport limestone.

It is noteworthy that the Manistique is correlated with the Rochester on Foerste's tentative opinion based upon the presence in it of the cephalopod genus *Huronia*.

T. E. Bolton (1953) has offered the latest revision of the Lower and Middle Silurian of southern Ontario, based on field work done in 1950 and 1951 under the auspices of the Geological Survey of Canada. He depresses the St. Edmund formation to a middle or lower Clinton horizon; proposes to raise the rank of the Fossil Hill beds to formation status with middle or lower Clinton age; leaves an hiatus opposite the upper Clinton horizons and for the "Lockport" or Cumings' "Engadine" of Ontario he proposes the name *Amabel* formation. According to Bolton the St. Edmund

"is from 80 to 100 feet thick on Manitoulin Island" and is separated from the overlying Fossil Hill dolomite by a 2 to 4 foot transition zone. "On the basis of the brachiopods *Stegerhynchus* (?) *Winiskensis* and *Rhynchospira lowi* the St. Edmund is correlated with similar zones in the Hendricks dolomite of northern Michigan. . . ."

The writer defined the St. Edmund dolomite from exposures near Cabot Head on the Bruce Peninsula. There it consists of massive dolomite 8 feet thick containing *Favosites cristatus* and *Atrypa parksi*. "Four feet of soft green shale intervenes between the top of the St. Edmund and the base of the Lockport dolomite which is thin bedded. . . ." "On Manitoulin Island this dolomite has not been recognized and appears to be absent."

Bolton follows Cumings in placing thick sections of dolomite on Manitoulin Island in the St. Edmund formation, but the fossils which he lists have no relation to those at the type locality. He says "Dense dolomites of the St. Edmund formation are relatively barren." The water-gap between Cabot Head, the type locality for the St. Edmund dolomite, and Fossil Hill is 42 miles, and Fitzwilliam Island which intervenes is 27 miles from Cabot Head, and appears to lack the St. Edmund dolomite.

The age of the St. Edmund is probably upper Clinton according to Ulrich and Bassler (1923): "The Mayville and Dyer Bay dolomites probably belong in the lower half of the Clinton group. . . ."

They state further "the *Mastigobolbina lata* zone is the most typical and persistent part of the Middle Clinton. According to this ostracod evidence, then, it appears that the Dyer Bay dolomite corresponds to the latter part of the Lower Clinton or the early part of the Middle Clinton with the former interpretation the more likely of the two." This suggests a correlation with the Wolcott dolomite. The Wingfield shale overlies the Dyer Bay dolomite and the St. Edmund dolomite overlies the Wingfield shale. The St. Edmund dolomite is therefore probably high up in the Clinton, possibly upper Rochester.

The real point at issue now has to be considered. Bolton follows Cumings in correlating the Fossil Hill beds with the Manistique formation of Michigan and raises them to the rank of a formation. He says:

> The name Fossil Hill is here adopted for the thin-bedded, fossiliferous dolomites that rest directly on the St. Edmund dolomite, in the numerous exposures around Fossil Hill, west of Manitowaning, Manitoulin Island. These dolomites were formerly referred to the Lockport by Williams (1919–37). Similar, thin-bedded, brown, fine-grained to crystalline dolomites may be identified from northern Michigan (Manistique formation) across Manitoulin Island and Bruce Peninsula to south of Orangeville. Exposures of argillaceous, dense Fossil Hill dolomites observed south of Orangeville could be traced south into lithologically similar dolomites that were definitely correlative with the Clinton Reynales formation. It is here proposed that these dolomites of the Fossil Hill formation are of Lower Clinton age, at least in Ontario Peninsula, and represent a northern facies of the Reynales. . . .
>
> The Fossil Hill formation is extremely fossiliferous. The brachiopod *Pentamerus laevus* is abundant at the base of the formation, but not entirely con-

fined to this horizon as in the Reynales; thick banks of this pentamerid outcrop on Bruce Peninsula. A prolific coral fauna, consisting of several species of *Favosites, Halysites, Arachnophyllum,* and *Syringopora* is contained in the upper beds.

These Lower Clinton Fossil Hill dolomites are the direct correlative, lithologically and faunally, of the Manistique formation of northern Michigan.

A number of questions are raised by the statements quoted above.

1. Is the Fossil Hill *formation* a mappable unit, as the definition of a formation requires?

2. Is the stratigraphic evidence offered by Bolton for the correlation of the Fossil Hill beds with the Clinton (Reynales) of New York state convincing?

3. What is Bolton's palaeontological evidence?

4. What is the significance of the Fossil Hill fauna?

These questions will be dealt with in order.

1. The Fossil Hill "formation" cannot be mapped from Bolton's description. The writer has spent much time around Fossil Hill and over the outcrops of the Lockport formation to the west and south, and is firmly convinced that the coral beds are too widely and irregularly distributed both horizontally and vertically to be mapped as a formation. The section measured by the writer at Fossil Hill illustrates the problem.

2. How convincing is Bolton's stratigraphic evidence for the correlation of the Fossil Hill beds with the Reynales formation of New York state? The writer's section at Fossil Hill shows that the coral beds are reef or lens-like bodies in thick-bedded dolomite, not in "thin beds" as described by Bolton. No evidence is given to prove that the Orangeville beds are of Fossil Hill age and the localities are 150 miles apart. The writer was unable to trace the Reynales dolomite farther north than Kelso, and Caley says "The Clinton formation extends along the face of the Niagara escarpment from Niagara River to a short distance north of Dundas, where it pinches out and disappears." Orangeville and Dundas are 50 miles apart.

Bolton's statement that "similar, thin-bedded, brown, fine-grained to crystalline dolomites may be identified from northern Michigan (Manistique formation) across Manitoulin Island and Bruce Peninsula to south of Orangeville," meets the criticism already stated above. The Fossil Hill beds are not "thin beds" but variable beds, mostly thick, with coral beds and reefs of typical species of organisms. Bolton's statement includes a stratigraphic correlation along 300 miles of outcrops broken by three water-gaps west of Manitoulin Island and a 24-mile water-gap north of Bruce Peninsula. The result is the correlation of the Manistique with the Lower Clinton, whereas Cumings and Ehlers correlate it with the upper Rochester, the DeCew limestone, and an hiatus below the Lockport. Such are the anomalies based upon long-range stratigraphic correlation!

3. What is Bolton's palaeontological evidence? He states: ". . . *Penta-*

merus laevis is abundant at the base of the formation, but not entirely confined to this horizon as in the Reynales; . . . . A prolific coral fauna, consisting of several species of *Favosites*, *Halysites*, *Arachnophyllum*, and *Syringopora*, is contained in the upper beds."

As shown above, at Fossil Hill the main *Pentamerus* zone is 80 feet above the main Fossil Hill beds, and only about 25 feet below the highest corals. Bolton stresses the importance of the *Pentamerus* beds in view of their occurrence in the Reynales formation at Rochester and vicinity. The writer, Cumings, and Bolton have recorded the densely packed beds of *Pentamerus* near the base of the "Lockport" at Owen Sound, Wiarton, Lion Head, Dyer Bay, and Cabot Head. Only the writer has noted that this is not the case on Manitoulin Island, where *Pentamerus* occurs at different horizons mostly much higher up in the dolomite formation. Casts of *Virgiana* in the Dyer Bay dolomite may have caused confusion in the past. The writer found *Pentamerus* at Wiarton in a second zone 125 feet above the base of the formation, and it appears to be this horizon which is represented at Fossil Hill. The statement quoted above, that "*Pentamerus laevis* is abundant at the base of the formation," has not been found to be true at the type locality, Fossil Hill, where it occurs well above the coral horizon.

Newberry reports *Pentamerus oblongus* as abundant in the Guelph division of the Niagara at Hillsboro, Ohio (Clarke & Reudemann, 1903, p. 132). Butts reports this species in the Louisville limestone of Jefferson County, Kentucky. Hartnagel (1907, p. 14) says "from Wolcott in Wayne county . . . west to beyond the Genesee the large brachiopod *Pentamerus oblongus* is very characteristic. . . . This fossil becomes less abundant in going west from Rochester and at Niagara it is not found though farther west in Ohio and Indiana it occurs in the Clinton strata and again higher up in the Guelph limestone."

The fact that this is one of Sowerby's species indicates it is widespread geographically. As most of the specimens north of the Niagara River are preserved as casts, the identity of the species may be questioned. This issue was raised by C. Schuchert when he and the writer were in the field together in 1912 and 1913. Hall and Clarke (1894, p. 237) refer to the variability of the species and state: "In New York this species is not known outside of the Clinton fauna, but passing westward, it abounds in the dolomites which bear a Niagara fauna in the states of Ohio, Indiana, Illinois, Wisconsin and Iowa." Cumings (1939) does not venture to name the species but calls it "a large species of *Pentamerus*." Gillette (p. 16) says: "Pentamerus is found in . . . the Reynales and the Wolcott limestones [of New York], . . . restricted to very definite portions within the formation. . . . The sporadic occurrence of the Pentamerus certainly suggests strongly that they required a very special type of ecology."

4. What is the significance of the Fossil Hill fauna? It seems noteworthy that the ages of the Engadine, Racine, Manistique, Attawapiskat, and other reef-bearing formations have been settled on the basis of faunal evi-

dence; but in the case of the Fossil Hill beds, stratigraphic evidence has been called upon almost exclusively, and that over hundreds of miles of lineal outcrops separated by many miles of overburden and water-gaps.

What have the fossils to say for themselves? At Fossil Hill, the writer reported 6 species of hydrozoa, 32 species of corals, and 6 species of brachiopods. Of these, three species of corals and one brachiopod are reported from the Lockport at Niagara River, only 18 miles from the type locality, Lockport, New York; and 8 of the species of corals and 4 of the brachiopods are reported from the "Lockport" at near-by Thorold. At Hamilton, 4 stromatoporoids common at Fossil Hill, were found in higher "Lockport" beds. At Cabot Head, 2 species of corals and one brachiopod were found in the basal "Lockport" beds; 8 coral species 30 feet up; and 7 species of corals high up. It is noteworthy also that at Guelph, just below the base of the Guelph formation at its type locality, 7 species of corals and one species of brachiopod common at Fossil Hill were found in the reef limestone and Eramosa beds.

Williams (1919) says: "The Gasport is 20 to 28 feet thick at Thorold and is composed largely of coral reefs which are full of fossils . . . corals, 9 genera, 13 species; crinoids, 2 genera, 2 species; brachiopods, 14 genera, 22 species; gastropods, 1 genus, 1 species; cephalopods, 1 genus, 1 species; trilobites, 2 genera, 2 species."

Cumings (1939) says the Gasport member has "an abundant fauna of crinoids, corals and brachiopods, the latter being mostly Rochester species. *Enterolasma caliculum*, *Alveolites thoroldensis*, *Coenites juniperinus*, *Pereichocrinus speciosus*, *Ichthyocrinus laevis*, and *Eucalyptocrinus muralis* are characteristic."

As listed by Butts, 19 species of corals and 3 of brachiopods are common to the Louisville limestone of Kentucky and Fossil Hill. Were other Fossil Hill occurrences to be considered, the number would doubtless be much greater. The "Lockport" of Ontario (Williams) and the Louisville (Butts) have the following in common: Corals—22 species and 7 other genera; Cystoidea—1 genus; Brachiopods—16 species and 3 other genera; Gastropods—1 species and 2 other genera; Cephalopods—1 genus. Butts concludes (p. 99) "there seems no reason for assigning the Louisville a younger age than upper Lockport. . . ." Foerste in the correlation chart (Swartz *et al.*, 1942) places the Louisville limestone in southern Indiana and northern Tennessee opposite the Cordell dolomite of the upper Manistique formation of northern Michigan and eastern Wisconsin.

According to Rominger, there are 22 coral species common to the Fossil Hill horizon and the beds from which his fossil corals of Michigan came. Lowenstam says (p. 482):

> In the Northern Peninsula of Michigan reefs are unknown in the Manistique deposits, and occur first, as far as known, well above the base of the overlying Engadine formation.
>
> By Racine-Guelph time, the density and areal extent of the reefs reached a

maximum, and an archipelago that extended from the border of the Ozark island northeastward at least as far as southern Ontario and probably as far as Hudson's Bay, was formed.

The only species of fossils common to the Fossil Hill horizon and the Clinton, Reynales dolomite are *Pentamerus oblongus*, *Stegerhynchus neglecta*, and *Favosites niagarensis*. The first two occur also in the *Irondequoit* dolomite. The Fossil Hill beds and the Rochester shale have the following in common:

Striatopora flexuosa,
Favosites niagarensis,
F. hisingeri,
Atrypa reticularis, and
Camarotoechia (*Stegerhynchus*) *neglecta*.

After making all due allowance for the different facies, the evidence weighs heavily against an older Clinton age for the northern coral horizons. Although the near-shore southern seas were probably unfavourable for most corals, the northern environment should have been favourable for at least some of the molluscs, and brachiopods.

The faunal analysis given above strongly favours a high Niagaran age for the Fossil Hill beds. They belong within deposits laid down by coral-bearing seas which according to Lowenstam were swept by strong southerly winds. The subsiding basin was evidently deepest in the northern Great Lakes syncline and there the section is thickest.

Conclusions

The Silurian formations of Ontario north of Cataract Junction were deposited in a northern sea and vary radically from the formations of New York State where the type American sections are located. The Georgian Bay sections have much in common with those of Michigan into which they merge. The Michigan formations are correlated with the New York sections on faunal evidence, and it is faunal evidence which is the final arbiter for the Ontario sections. Stratigraphically, Michigan can gain more from Ontario than Ontario can gain from Michigan, because Ontario occurrences intervene between New York and Michigan.

The age of the Fossil Hill beds must be considered in relation to the Silurian section of which they form a part. On this basis the section in the Bruce Peninsula and Manitoulin Island may be correlated from below upward as follows: Manitoulin dolomite and Cabot Head shale, Cataract (Medina) in age; Dyer Bay dolomite, Clinton (Reynales-Wolcott) in age; Wingfield shale, Clinton (Irondequoit)? in age; St. Edmund dolomite, Rochester-DeCew? in age; Undivided "Niagara limestone," "Lockport" of Williams or "Manistique" and "Engadine" of Cumings, and including Bolton's "Fossil Hill" and "Amabel" formations, upper Rochester to Eramosa in age. The lower part, at least, of the Fossil Hill beds may be equivalent in age to the Gasport limestone of New York State.

The above tentative correlation suggests the need for a revision of terminology for the Silurian of the Georgian Bay region. The Fossil Hill "formation" should be reduced to member rank equivalent to Lion Head, Colpoy Bay, Wiarton, and Eramosa. Cumings has suggested that Eramosa be raised to formation rank, and the wide extent and persistent characters of this division make its claim worth consideration.

The name "Manistique" is foreign to Ontario and too far from its type section to be acceptable. "Amabel" could be enlarged to include the section formerly designated the "Niagara limestone." The distribution, character, and thickness of the St. Edmund formation on Manitoulin Island have yet to be determined.

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